

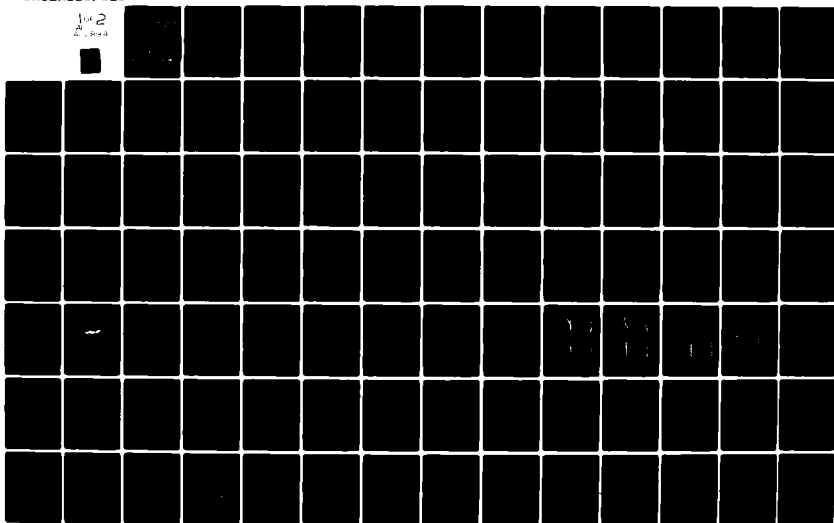
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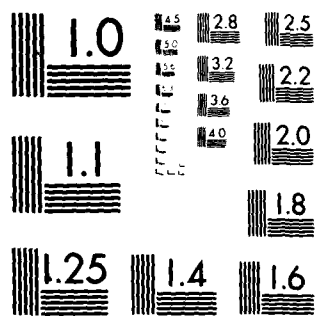
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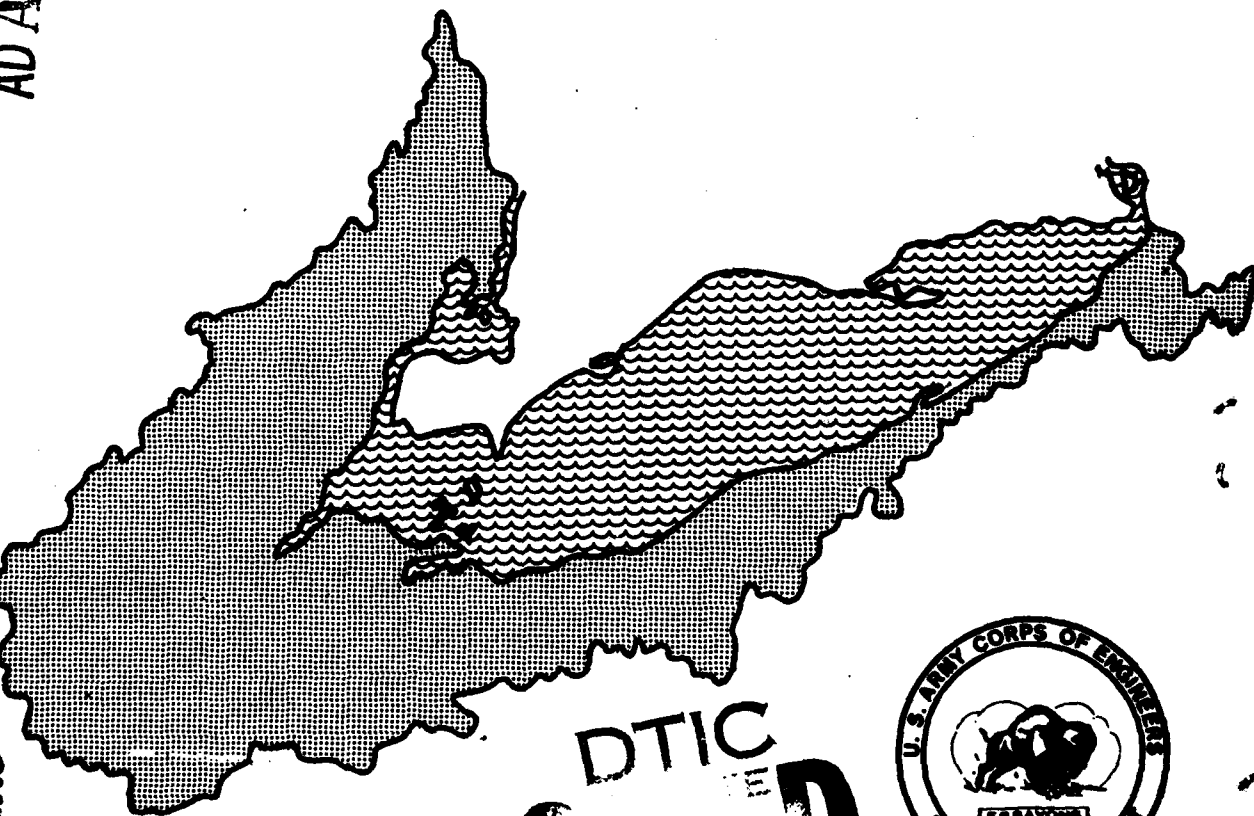
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TECHNICAL REPORT SERIES

FLUVIAL TRANSPORT AND PROCESSING OF SEDIMENT AND NUTRIENTS IN LARGE AGRICULTURAL RIVER BASINS

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FLUVIAL TRANSPORT AND PROCESSING OF
SEDIMENT AND NUTRIENTS IN
LARGE AGRICULTURAL RIVER BASINS

by

David B. Baker
Water Quality Laboratory
Heidelberg College
Tiffin, Ohio 44883

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SECTION 1

INTRODUCTION

In comprehensive studies of Great Lakes pollution from land use activities, the large agricultural river basins of northwestern Ohio stand out as major problem areas (IJC, 1980a). These basins contribute high unit area yields of sediment, phosphorus, and nitrogen to the western and central basins of Lake Erie. The high sediment and nutrient yields are associated with intensive row crop agriculture on the fine textured soils of this region. Agriculturally-derived nutrients, coupled with the point source nutrient loading from the area's population centers and the morphometry of the Lake Erie basin, have resulted in accelerated eutrophication of these waters and associated water quality problems.

The Maumee, Portage, Sandusky and Huron Rivers of northwestern Ohio have been the sites of detailed studies of nutrient and sediment transport. Initially these studies were aimed at determining the total loading of nutrients and sediments from these rivers into Lake Erie, so that both total loads and the relative contributions of point and nonpoint sources could be determined. By 1975, it became evident that nonpoint sources accounted for more total phosphorus inputs into Lake Erie than point sources, and that point source controls would be inadequate to achieve the phosphorus load reductions considered necessary to reverse the eutrophication of Lake Erie (COE, 1975).

In 1975, the river transport studies within the Sandusky River Basin were expanded to include a network of nine stations, including six large tributary watersheds and three mainstream stations. The expanded studies were aimed at identifying critical watersheds with respect to sediment and nutrient yields and to study the effects of mainstream transport processes on the delivery of both point and nonpoint-derived pollutants to the lake.

Concurrently with the river transport studies, detailed studies were being conducted to determine the applicability of various agricultural best management practices for reducing nutrient and sediment losses from cropland in these river basins (COE, 1979). These studies concluded that a variety of conservation tillage practices, including no-till, could significantly and economically reduce phosphorus loading to Lake Erie. A major tillage demonstration project was initiated in the Honey Creek Watershed of the Sandusky Basin under the direction of a Joint Board of Soil and Water Conservation District Supervisors and supported by both the U.S. Army Corps of Engineers and the Agricultural Stabilization and Conservation Service. The results of the Honey Creek Project, and other tillage demonstration projects in the area, suggest that many of the area's soils are suitable for conservation tillage management and that these methods, when properly implemented, offer economic advantages to farmers (Honey Creek Joint Board, 1980; Allen County Soil and Water Conservation District, 1980).

The major impetus for transition to conservation tillage in this area is likely to be the economic advantages these methods provide to farmers. In adopting these methods, farmers are simultaneously implementing an agricultural nonpoint source pollution abatement program in an area where adverse impacts of agriculturally derived pollutants on a major water resource have been documented. In recognition of these potential water quality benefits, the use of water quality management resources to facilitate rapid

and successful transitions to conservation tillage in this region has been initiated through agreements between Region V of the U.S. Environmental Protection Agency and the Ohio Department of Natural Resources. Thus, this region is about to move from demonstration projects to area-wide implementation programs.

In anticipation of changing agricultural technology in this region, an additional objective of the river transport studies has been to obtain adequate background data upon which to evaluate the effectiveness of best-management-practices in reducing sediment and nutrient export from large agricultural river basins. To date, the effectiveness of conservation tillage programs in reducing nutrient and sediment losses have been evaluated largely in plot or small watershed studies. Many questions remain to be answered concerning the effectiveness of these programs in reducing sediment and nutrient yields from large river basins (Bachmann, 1980). In particular, uncertainties about possible changes in delivery ratios, enrichment ratios, and bioavailability create parallel uncertainties about reductions in nutrient and sediment yields.

A major difficulty in documenting the environmental benefits of conservation tillage programs is the large annual variability in sediment and nutrient export by river systems. Consequently, considerable effort in these studies has gone into characterizing the variability in sediment and nutrient export at the transport stations. In addition a rainfall monitoring program has been established in the Sandusky Basin to provide more information for correlation with material export from the watersheds. Until the effectiveness of agricultural nonpoint controls is evaluated in connection with major, large scale implementation programs, efforts toward effective integration of point and nonpoint source control programs will be hampered.

Support for the collection of the data sets discussed in this report has come from many sources. These include: 1) research grants from the U.S. EPA for studies of flow augmentation (16080DFO 01/71) and river transport (R 805436-01-02); 2) contracts with the Toledo Metropolitan Area Council of Governments as part of their 208 Planning Study; 3) contracts with the Army Corps of Engineers for data collection in support of the Lake Erie Wastewater Management Study; 4) contracts with the Ohio Department of Natural Resources for upground reservoir management studies; 5) grants from the Rockefeller Foundation and the Soap and Detergent Association for studies of agricultural nonpoint pollution; 6) grants from the cities of Tiffin, Bucyrus, and Upper Sandusky for evaluating instream benefits of phosphorus removal programs; and 7) support from Heidelberg College for matching funds and data collection during interim periods between external funding sources. The stream gaging programs operated by the U.S. Geological Survey with support from the Ohio Environmental Protection Agency, the Ohio Department of Natural Resources and the U.S. Army Corps of Engineers provided the flow data essential to these studies.

Given the support described above, it has been possible to develop what may be the most detailed data sets available in the United States for analyzing and characterizing the export of sediments and nutrients in large agricultural river basins. A major use of this data has been within the Lake Erie Wastewater Management Study (COE, 1979). The tributary loading data developed by the Corps of Engineers and based in large part on northwestern

Ohio rivers has been used by the International Joint Commission in developing phosphorus management strategies for the Great Lakes Basin. The data has also been used to develop and test river transport models as part of the Lake Erie Wastewater Management study (Verhoff, et al., 1978). These data were also used extensively in the Maumee Basin Pilot Watershed Report (Logan, 1978). Data from the Honey Creek watershed has been used in connection with testing the EPA's Nonpoint Source Model (Cahill, et al., 1979) and as part of an EPA-sponsored statistical correlation study of sediment-pollutant relationship (Zison, 1980). The Great Lakes Basin Commission selected the Sandusky Basin Data sets for illustrating the application of the Watershed Model for integrating point and nonpoint phosphorus control programs (Monteith, et al., 1980). The data have also been used in the Ohio EPA's Sandusky Basin 208 Study, in the Toledo Metropolitan Area Council of Government's 208 Study, and in local water quality planning programs by cities along the Sandusky River. The data are available in the STORET system. Data through the 1977 water year have been published by the Corps of Engineers (COE, 1978).

In this report background information on each of the watersheds is presented along with the methods used in the collection of the river transport data. The report includes both summary data on loading from each watershed, as well as, detailed examples of the characteristics of nutrient and sediment transport as it occurs in rivers of this region. Some implications of the data for water quality management planning programs are presented. The appendix includes a generalized river transport model based on an extension of the transport models developed in the Lake Erie Wastewater Management study.

SECTION 2

CONCLUSIONS

1. The unit area yields of phosphorus and nitrate from the river basins of northwestern Ohio are high relative to other agricultural watersheds. Most of the loading occurs during the short periods of time associated with storm flows. This area is the largest contributor of agriculturally-derived pollutants affecting the Great Lakes.
2. The concentrations of sediments, total phosphorus, and nitrates all tend to increase with increasing stream flow while the concentrations of chlorides and conductivities decrease with increasing flow. For all parameters studied except dissolved orthophosphorus, there are large differences between flux weighted mean concentrations and time weighted mean concentrations.
3. During individual storm events, the concentrations of sediments, total phosphorus and TKN generally show advanced peaks relative to the hydrograph peak while nitrates show a trailing peak. The latter is probably due to the delayed arrival at the gaging station of nitrate-laden tile effluents relative to surface runoff. Minimum conductivities and chloride concentrations occur simultaneously with the peak flows. Both resuspension associated with the passage of storm waves and routing of surface runoff account for the advanced sediment and total phosphorus peaks.
4. Storms with equal peak flows can have widely differing flux weighted mean concentrations of sediments, phosphorus, and nitrates. Furthermore the flux weighted mean concentrations did not show a significant increase as the peak flows increased. In contrast the flux weighted conductivity did decrease as peak storm flows increased.
5. The large variability in nutrient and sediment loads for storms of equal size suggest that material export is not limited by the transport capacity of the rivers but rather by the movement of materials from the land surface to the stream system. Thus, reductions in river export should accompany nonpoint control programs that reduce material transport from the land surface to the stream systems. Possible increases in stream bed or stream bank erosion associated with the sediment carrying capacity of the stream will not prevent the occurrence of load reductions associated with control programs.
6. There are large annual variations in both loading and flux weighted concentrations of sediments and nutrients at the transport stations. Both the total annual runoff and the proportion of winter to summer runoff affect the flux weighted mean concentrations in a given year. For most parameters the summer and winter periods yield significantly different concentration-flow relationships.
7. The total and particulate phosphorus to sediment ratios in individual samples are highly variable and decrease as the sediment concentrations increase. This gives rise to annual variations in the phosphorus to sediment ratios, depending in large part on the proportion of winter to summer runoff in a particular year.

8. Given large data sets, calculations of mean annual loading using flow duration tables are accompanied by small standard errors of the estimate. Consequently, if agricultural nonpoint control programs reduce loading by lowering the average concentrations occurring in various flow intervals, such reductions should be detectable in the study basins. These data sets provide baseline information upon which to judge the effectiveness of agricultural nonpoint control programs.
9. The sediment delivery ratios in the study watersheds range from 6.2 to 11.9% while average gross erosion rates vary from 4.2 to 9.4 T/ha/yr. The delivery ratios are not correlated with the size of the watershed but are inversely correlated with the gross erosion rate. There is no correlation between gross erosion rates and unit area nonpoint phosphorus yields. These observations raise doubts about the concept of "critical areas" and the use of gross erosion rates in their identification. The sediment and phosphorus yields from these large watersheds may be more related to the amount of clay entrained by rain drop impact and subsequent surface runoff. Tillage practices which increase cover and/or decrease runoff could reduce sediment and phosphorus yields from areas of both high and low gross erosion.
10. Several associated studies suggest that approximately 35% of the particulate phosphorus loading from northwestern Ohio rivers is bioavailable. Assuming that all of the dissolved reactive phosphorus is bioavailable, about 50% of the total phosphorus loading from these rivers is bioavailable.
11. Both concentration profiles and flux exceedency data indicate that point source phosphorus, most of which is in the form of soluble reactive phosphorus when it enters streams, is rapidly taken up into the stream sediments. There is indirect evidence that less than 100% of the point-source-derived phosphorus is subsequently delivered out of the stream system. Limited data suggests that the bioavailability of particulate phosphorus exported during storms is no greater from watersheds containing large point source phosphorus inputs than from watersheds that are strictly agricultural. Apparently the bioavailability of point-source-derived particulate phosphorus is no greater than that of nonpoint-source-derived particulate phosphorus.
12. Most of the soluble reactive phosphorus exported during storm events is derived from nonpoint sources. The short retention time of storm flows in the lower portions of rivers or in estuaries, bays and the nearshore zone may result in high deliveries of nonpoint-derived soluble phosphorus through these zones to the open lake. In contrast, point-source phosphorus entering these zones may be subject to deposition and transformation to less bioavailable forms.
13. Concentration exceedency data at the transport stations show that both nitrate and conductivities exceed the state's drinking water standards from two to five percent of the time. The highest nitrate concentrations occur in the spring and early summer when the rainfall duration and intensity result in a high proportion of tile effluent in comparison with surface runoff. Highest conductivities occur during winter low flow

periods.

14. Quality control testing done in connection with these studies show that, although significant changes in concentrations of soluble phosphorus and nitrate do occur during one week of storage without preservation, the changes are small relative to the errors in loading calculations associated with flow measurements or errors that would be introduced by less frequent sample collection.

SECTION 3

RECOMMENDATIONS

Documentation of the effectiveness of conservation tillage programs in reducing nutrient and sediment export from large agricultural river basins is needed before large scale, integrated, point-source/nonpoint-source control programs can be initiated. Existing demonstration projects in this region have shown that conservation tillage can be successful from the standpoint of crop production. The actual acreages currently committed to these management practices are, however, small in comparison to the extent of conventional tillage. Data at the transport stations discussed in this report are essentially baseline data reflecting nutrient and sediment export under conventional tillage programs.

Given the economic advantages of conservation tillage programs on several of the important soil types in this region, farmers throughout this area are likely to be adopting these practices. This will simultaneously constitute a gradual, area wide implementation of an agricultural nonpoint pollution control program. Evaluation of the environmental impacts of such a program will be difficult and require long term studies.

Where funds for water pollution abatement are being used to foster the adoption of conservation tillage programs, substantial portions of these funds should be directed toward specific, large watersheds. This should result in a more rapid conversion to conservation tillage in these watersheds and allow for an earlier assessment of environmental benefits, as well as any unforeseen environmental problems, that could accompany conservation tillage technology. Such an approach would also provide information on the feasibility and procedures for achieving a high proportion of conservation tillage in large watersheds.

In environmental assessments of conservation tillage programs in large watersheds, measurements of the bioavailability of particulate phosphorus and particle size analyses for suspended solids should be included. Also pesticide runoff measurements should be added since the tillage programs may well increase tile flow relative to surface runoff and thereby provide a rather direct pathway for the movement of soluble pesticides, as well as nitrates, to the stream system. The impact of changing agricultural technology on biological communities in the stream ecosystem should also be included in the assessment programs. It will also be necessary to monitor the changing distribution of tillage practices, both in the targeted watersheds and in adjacent control watersheds.

Data sets of the type developed in the Sandusky Basin should also be used to explore possible cost savings through time-variable management at municipal sewage treatment plants. Integrating flow augmentation from existing upground reservoirs with both point and nonpoint controls would provide the most effective and economical water quality management programs for this region. The application of the Watershed Model, as developed by the Great Lakes Basin Commission, should be considered for the Sandusky Basin. The concepts of the model, as it is applied to phosphorus, should be extended to other water quality parameters.

SECTION 4

DESCRIPTION OF THE STUDY AREA

LOCATION OF THE STUDY BASINS

This report includes data collected in the Maumee, Portage, Sandusky and Huron River Basins in northwestern Ohio. The Maumee and Portage drain into the western basin of Lake Erie, and the Sandusky and Huron empty into the southwestern corner of the central basin of the Lake (Figure 1). The drainage basins of these rivers and the associated areas draining directly into the lake have a total area of about 25,000 sq. km. or 45% of the land in the United States which drains into Lake Erie. It has been estimated that these rivers account for 73% of the agriculturally derived sediments which enter Lake Erie from the United States and for 39% of the agriculturally derived sediments entering the entire Great Lakes system from the United States (PLUARG, 1974). The primary focus of this study is the Sandusky River Basin which contains a network of 10 river transport stations.

GEOLOGY

The geology of the Sandusky River Basin has been described in detail by Forsyth (1975). The basin occupies glacial plains composed of ground moraine crossed by the Defiance, Fort Wayne, and Wabash end moraines (Figure 2). North of Tiffin and in several isolated areas in the southern part of the Basin, the glacial till is overlain by glacial lake sediments. Alluvial soils are restricted to narrow bands along the stream systems. The underlying bedrock is mostly Silurian-Devonian carbonates, with Devonian shale and sandstone in the southeast (Figure 3). The topography is relatively flat except for the areas occupied by the end moraines and where streams have cut through the glacial till.

SAMPLING STATIONS

Most of the stream transport studies have been conducted at the 12 USGS stream gages listed in Table 1. The stations on the Maumee, Portage and Huron Rivers and the Fremont station on the Sandusky are located at the stream gaging stations nearest Lake Erie where tributary loading data for the lake are collected. A short distance downstream from these gaging stations estuarine-like conditions develop in each of these rivers. On the Maumee, Portage and Huron rivers the samples were collected at chemical monitoring stations located near the stream gage rather than at the gage itself. In the Sandusky network of stations, all of the samples were collected at the stream gaging stations. The locations of the river mouth stations and the Sandusky network of stations are shown in Figures 4 and 5. The drainage area, period of hydrological record, and average discharge for each station are listed in Table 1.

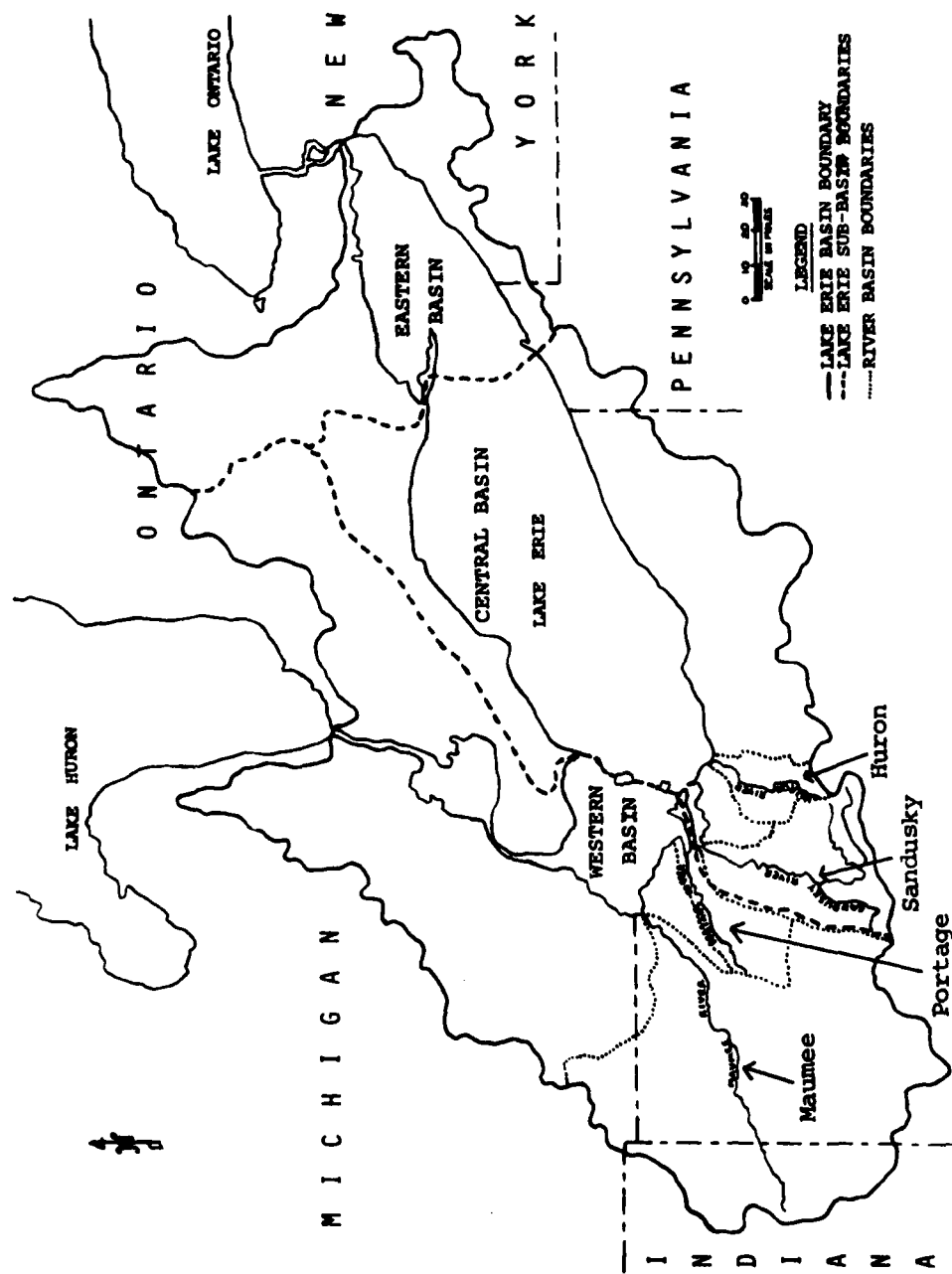


Figure 1. Location of the northwestern Ohio river basins in relation to Lake Erie.

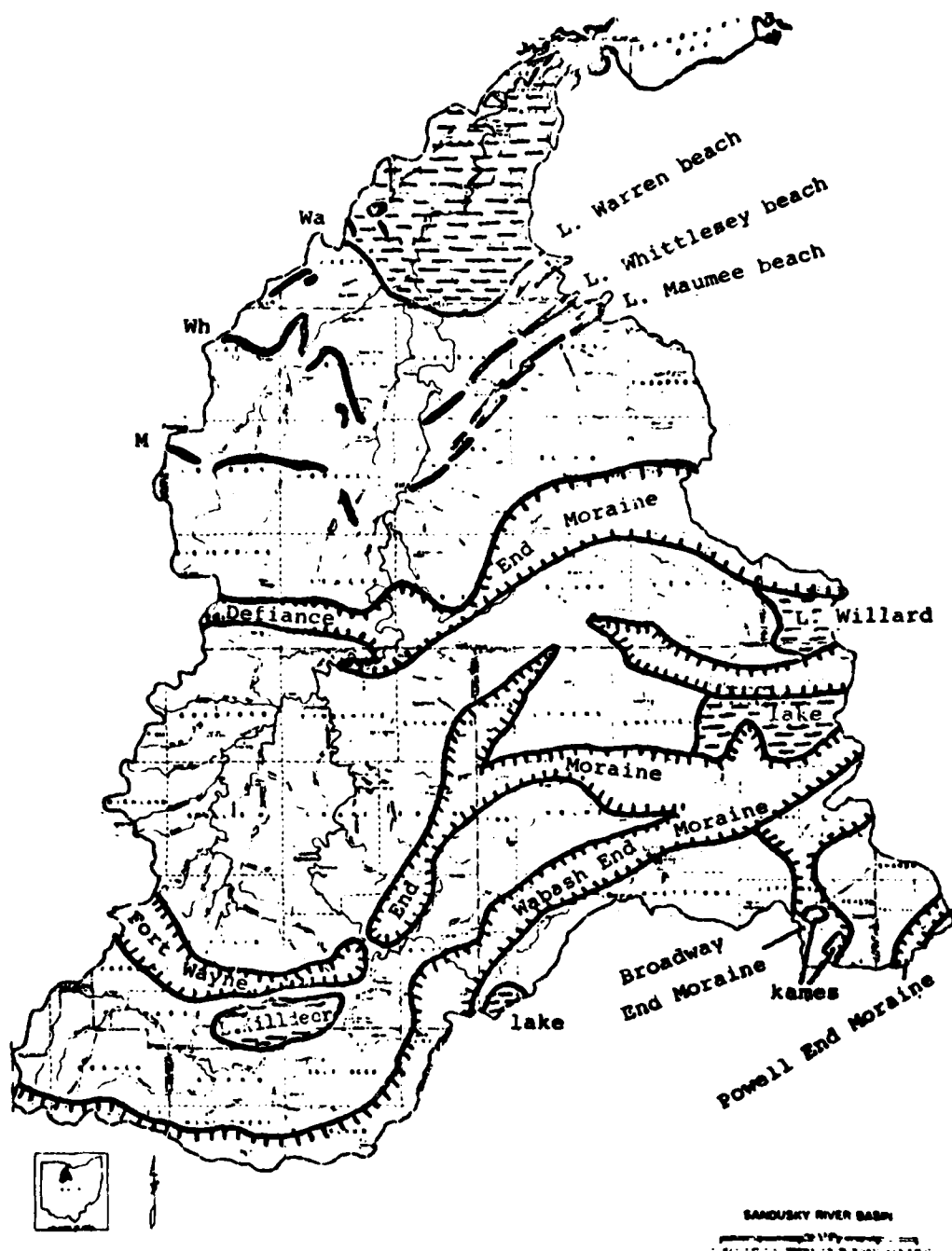


Figure 2. Glacial map of the Sandusky River Basin area. Glacial deposits shown are end moraines (enclosed by hashures and named), ground moraine (left white), lake beaches (marked by black bands and named), and lake-bottom silts and clays (identified by horizontal-dash pattern). Areas of alluvial deposits along the Sandusky River and its tributaries are too small to be shown on this map. (After Forsyth, 1975).

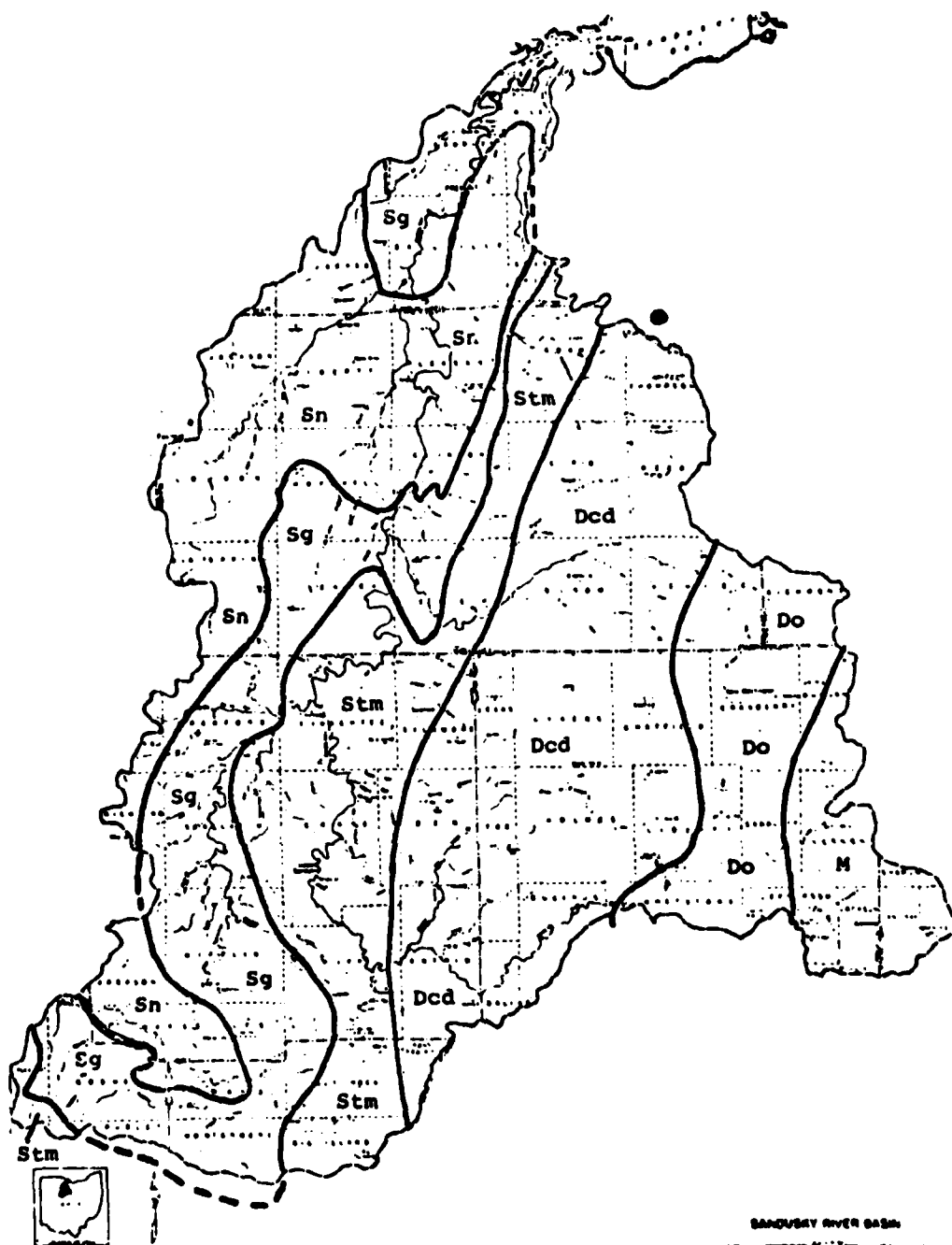


Figure 3. Bedrock geologic map of the Sandusky Basin area. Bedrock units are identified by the following symbols.

- M - Mississippian Berea Sandstone (and other Mississippian units)
- Do - Devonian Ohio Shale
- Dcd - Devonian Columbus and Delaware Limestones
- Stm - Silurian Tymochtee and "Monroe" Dolostones
- Sg - Silurian Greenfield Dolostone
- Sr - Silurian Niagaran-aged Lockport Dolostone

All these rock units are dipping very gently to the east, as a result of their location on the east limb of the Cincinnati Arch. (After Forsyth, 1975).

Table 1. Locations, station numbers, areas, periods of hydrological record, and average discharge for stream transport stations in northwestern Ohio. (USGS, Water Quality Records for Ohio, Volume 2, 1979).

Stream	Gaging Station		Sampling Station		Area Km ²	Period of Record * Yrs.	Average Discharge	
	Location	I.D.	Location	I.D.			m ³ /s	mm/yr.
Maumee	at Waterville	04193500	near Waterville	04193490	16,395	54	136.4	262
Portage	at Woodville	04195500	in Woodville	04195600	1,109	47	8.836	251
Sandusky	near Bucyrus	04196000	same as gaging station	04196000	230	38	2.438	355
Broken Sword	near Nevada	04196200	same as gaging station	04196200	271	3.5	2.45**	285**
Sandusky	near Upper Sandusky	04196500	same as gaging station	04196500	722	55	6.88.	281
Tymochtee	at Crawford	04196800	same as gaging station	04196800	593	15	4.814	256
Sandusky	near Mexico	04197000	same as gaging station	04197000	2,005	53	16.40	258
Honey Creek	at Melmore	04197100	same as gaging station	04197100	386	3.5	3.32**	271
Wolf Creek West Br.	at Bettsville	04197300	same as gaging station	04197300	171.5	3.5	1.42**	261
Wolf Creek East Br.	near Bettsville	04197450	same as gaging station	04197450	213	3.5	2.26**	334
Sandusky	near Fremont	04198000	same as gaging station	04198000	3,240	53	27.15	264
Huron	at Milan	0419000	Below Milan	04199100	961	29	8.524	280

*Period of record through the 1979 water year.

**Estimated by comparison to nearby long term stations.

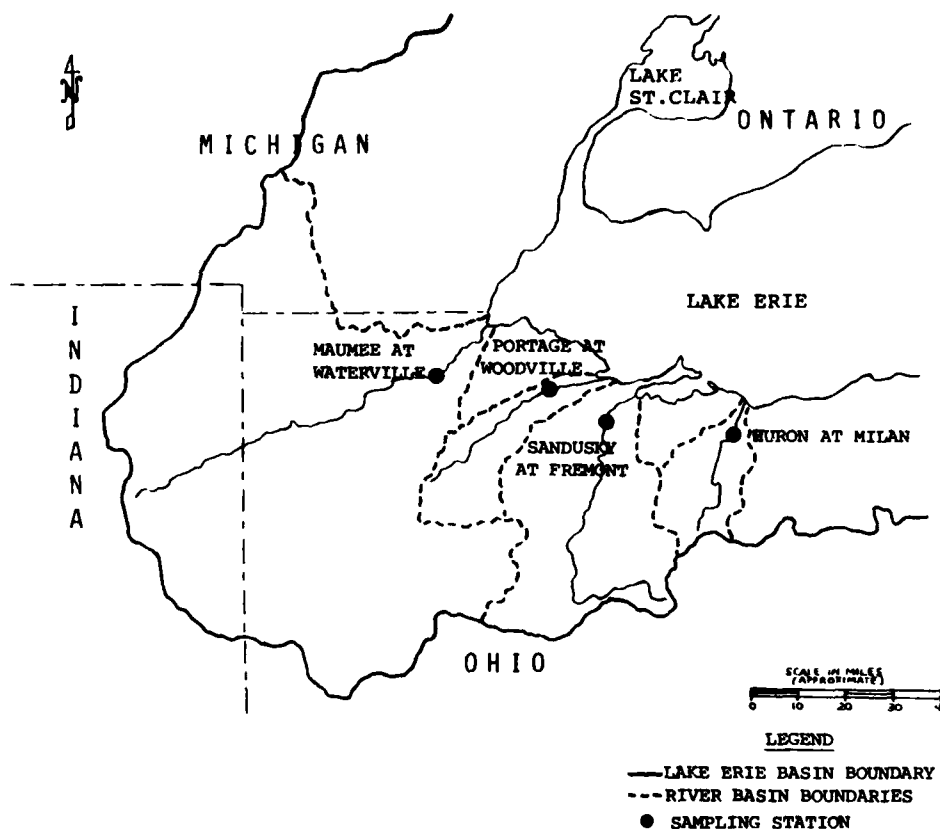


Figure 4. Location of tributary mouth sampling stations for Lake Erie loading studies from northwestern Ohio rivers.

WATERSHED CHARACTERISTICS

As part of the Lake Erie Wastewater Management Study a computerized land-use/land-capability data base was assembled for the entire United States portion of the Lake Erie Basin (COE, 1979). The data base was organized using the Land Resource Information System (LRIS) as developed by Resource Management Associates (Bliss et al., 1975). This system is based on a cellular data file containing information on land use, soils, and locations including watershed and county affiliations. Within each cell the information is coded for a particular point. The locations of the points are determined using a systematic unaligned approach in which randomly selected coordinates within the cells of the first row and column of the cellular grid establish the position of the points in the remainder of the cells (Bliss et al., 1975).

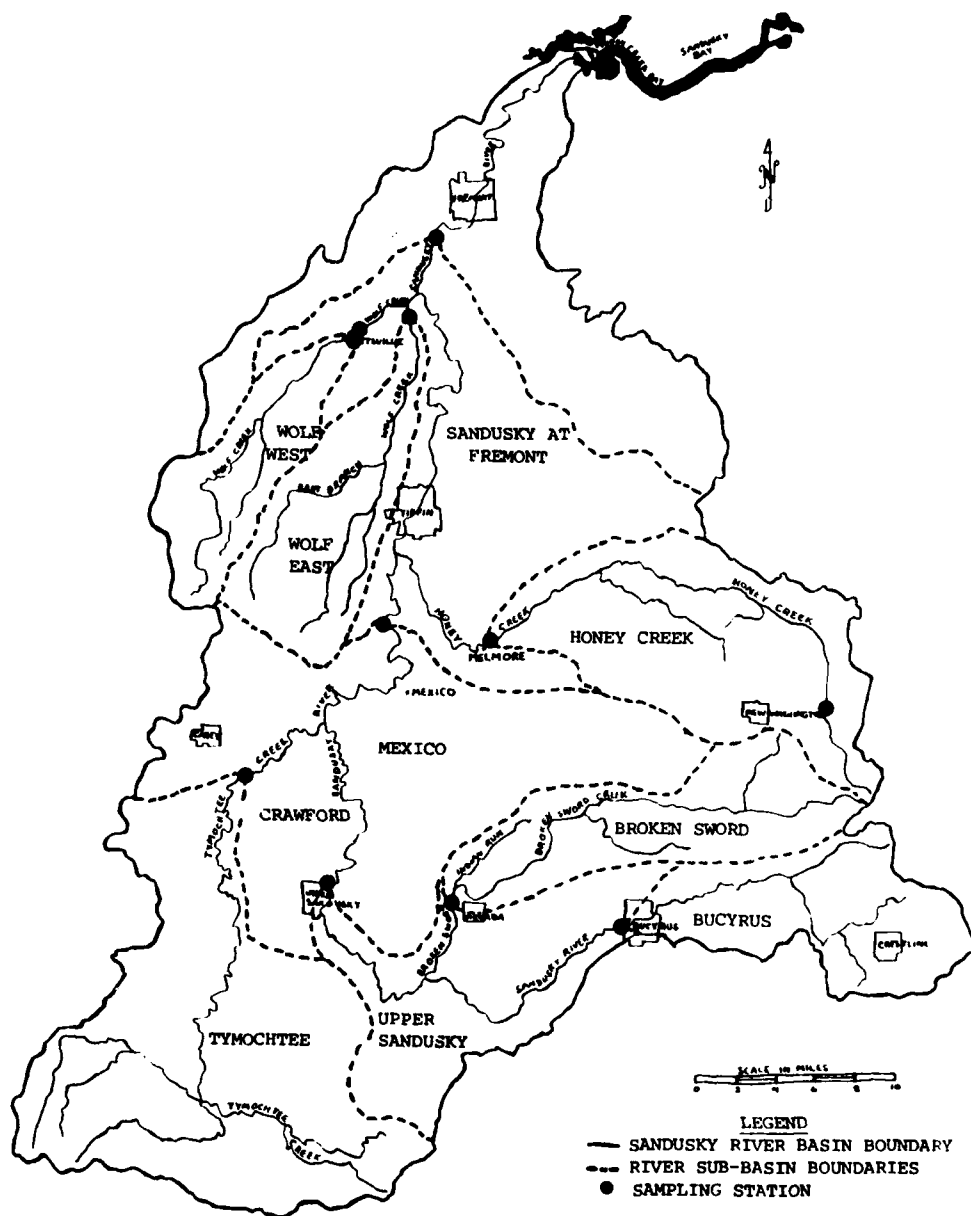


Figure 5. Location of sampling stations in the Sandusky Basin network of river transport stations.

In the Sandusky Basin which was selected for more detailed studies, the cells are 300 m on a side (9 hectares) except for the Honey Creek and Rock Creek watersheds and the Sandusky County portion of the basin where the cells are 200 m on a side (4 hectares). Thus in the Sandusky Basin above the Fremont gaging station, approximately 45,000 cells and points have been encoded. For the Portage River Basin 4 hectare cells were used while for most of the Maumee and Huron River Basins 36 hectare cells were encoded.

The LRIS system has been used to produce a variety of summary tables and maps for watersheds and counties. These tables or maps can reflect: single features, such as land use, slopes, or soil texture; or co-occurrences of features, such as cropland on sloping soils with high erodibility (RMA, 1979).

The land use in the watersheds above each of the sampling stations is summarized in Table 2. Land use was encoded through photointerpretation of

Table 2. Percentage distribution of major land uses in the study basins.

Location	Total Area km ²	Cropland %	Pasture %	Forest %	Water %	Other %
Maumee, Waterville	16,395	75.6	3.2	8.4	3.5	9.4
Portage River, Woodville	1,109	85.5	3.6	5.6	0.9	4.3
Huron River, Milan	961	75.3	3.5	12.5	2.2	6.4
Sandusky River, Fremont	3,240	79.9	2.3	8.9	2.0	6.8
Sandusky River, Mexico	2,005	80.3	2.3	8.7	2.1	6.6
Sandusky River, Upper	772	78.0	3.4	9.1	2.0	7.5
Sandusky River, Bucyrus	230	73.3	4.9	9.4	2.1	10.2
Tymochtee Creek Crawford	593	84.0	1.2	7.6	2.2	4.8
Honey Creek, Moremore	386	82.6	0.6	10.0	0.5	6.3
Broken Sword Creek, Nevada	217	84.7	1.4	8.5	1.3	4.1
Wolf East, Ft. Seneca	213	81.9	2.7	6.3	2.0	7.0
Wolf West, Bettsville	171.5	83.3	1.4	4.7	3.1	7.6

high altitude infrared photographs taken by NASA, Lewis of Cleveland, Ohio in June, 1976. The 70,000 to 1 scale photographs were interpreted by the Environmental Research Institute of Michigan, Ann Arbor, Michigan. The land use categories presented in Table 2 are composite categories of more than 50 separate land uses encoded from the photographs. The dominance of cropland for all of the watersheds is evident.

Soils information was taken from modern soil surveys where these were available. The soil phase and slope classifications were recorded for each point. A soils properties file containing the physical/chemical properties for each soil was used in conjunction with the soil phase data.

The percentage of land in each watershed falling within various slope classifications is shown in Table 3. For each soil phase, unique slope values were assigned. These values represented the median value of all slopes observed on that soil during the 1% National Erosion Survey of 1977-78 conducted by the Soil Conservation Services. The dominance of level and gently sloping lands within the region is evident. There are, however, some substantial differences in the proportions of soils in the 0.2%, 1% and 3.5% slope classes among the various watersheds.

Tables 4, 5 and 6 show the composition of these watersheds in terms of soil textures, drainage characteristics and soil erodibility. All of these are taken directly from the soil properties files. Generally fine textures, poor drainage and high erodibility characterize all of the watersheds. The Maumee, Portage, and Wolf-West basins have somewhat finer textured soils than the Sandusky and Huron basins. They also have higher percentages of soils in the very poorly drained category. In all of the watersheds, tile systems are used extensively to improve drainage and allow timely field operations.

Co-occurrences of the above watershed features have been published for all of the major river basins of Lake Erie and for all of the Sandusky River Basin watersheds (RMA, 1979 b, c). These dual feature summaries include:

1. Land Use and Soil Permeability
2. Soil Permeability and Slope
3. Land Use and Slope
4. Land Use and Soil Texture
5. Soil Texture and Slope
6. Slope and Soil Erodability
7. Soil Texture and Erodability
8. Land Use and Erodability
9. Land Use and Soil Drainage Class
10. Land Use and Soil Capability Class

The LRIS system has also been used for producing colored maps which display such features as land use, surface texture, slope and potential gross erosion for the Lake Erie Basin (COE 1979) and for the Honey Creek watershed (Cahill and Pierson, 1979). Suitability maps for contour cropping and no-till corn production have also been produced for Honey Creek. As part of the LEWMS study, sets of maps and summary tables are being produced for each county in the U.S. portion of the Lake Erie Basin. In addition the maps and tabular summaries will be aggregated into watershed boundaries for 5 river basins, one of which is the Sandusky Basin. These maps are extremely useful in identifying potentially critical areas and in planning appropriate nonpoint pollution abatement programs.

Table 3. The areal percentage of lands in various slope classifications for the study watersheds.

Watershed	Slope Classification									
	less than 0.2%	0.5%	1.0%	2.0%	3.5%	6-8%	9-11%	12-14%	15-17%	18% or greater
Maumee	42.7%	9.9%	18.7%	1.5%	23.8%	0.1%	2.3%	0.2%	0.5%	0.3%
Portage	57.2	13.9	1.5	1.4	23.5	1.7	0.9	0.0	0.0	0.0
Sandusky (Bucyrus)	15.9	8.6	35.2	0.0	33.7	0.0	4.8	0.0	0.6	1.1
Broken Sword	11.1	8.9	33.6	0.0	40.6	0.0	5.4	0.0	0.1	0.3
Sandusky (Upper Sandusky)	18.4	9.3	31.3	0.0	34.7	0.0	4.6	0.0	0.8	0.9
Tymochtee	34.0	8.4	35.7	0.1	17.9	0.0	2.4	0.0	1.0	0.6
Sandusky (Mexico)	21.4	8.9	34.4	0.1	29.2	0.0	3.9	0.0	1.1	1.0
Honey Creek (Melmore)	6.9	7.8	49.0	4.6	29.2	0.7	1.7	0.0	0.0	0.0
Wolf Creek (West)	46.3	1.7	41.7	0.0	10.3	0.0	0.0	0.0	0.0	0.0
Wolf Creek (East)	16.2	2.7	63.4	0.0	17.7	0.0	0.0	0.0	0.0	0.0
Sandusky (Fremont)	19.0	8.2	38.8	0.8	28.8	0.1	3.1	0.0	0.7	0.6
Huron	2.7	11.0	18.0	43.8	7.8	13.9	0.7	1.5	0.3	0.4

Table 4. Percentage distribution of soil textures in the study watersheds.

Watershed	Soil Texture											
	Clay	Silty Clay	Silty Clay Loam	Clay Loam	Sand Clay Loam	Loam	Silty Loam	Sandy Loam	Fine Sandy Loam	Fine Sand	Loamy Fine Sand	Muck
Maumee	18.5%	4.5%	23.8%	1.4%	0.4%	15.0%	26.2%	4.2%	2.0%	0.6%	1.6%	1.2%
Portage	46.3	0.0	10.5	2.3	6.6	11.3	12.4	0.9	3.6	0.1	6.0	0.0
Sandusky (Bucyrus)	0.0	0.0	15.9			1.3	82.1	0.0	0.8		0.0	0.0
Broken Sword	0.0	0.0	13.5			3.7	81.5	0.1	1.2		0.0	0.0
Sandusky (Upper Sandusky)	1.0	0.3	19.0			3.1	75.2	0.1	1.3		0.0	0.1
Tymochtee	4.4	3.3	34.1			0.6	56.4	0.6	0.5		0.0	0.2
Sandusky (Mexico)	1.5	1.1	22.3			3.0	70.2	0.4	1.1		0.0	0.3
Honey Creek (Melmore)	0.0	0.2	18.7			2.2	76.1	0.0	0.5		0.0	2.2
Wolf Creek (West)	0.0	0.0	52.3			4.9	42.4	0.0	0.2		0.0	0.0
Wolf Creek (East)	0.0	0.2	31.0			4.7	63.4	0.0	0.2		0.4	0.0
Sandusky (Fremont)	1.3	0.7	22.2	0.2	0.0	4.7	68.0	0.3	1.1	0.1	0.5	0.5
Huron	0.0	0.4	16.1	0.0	0.0	11.1	65.6	0.6	2.6	0.1	1.6	2.0

Table 5. Percentage distribution of soils falling into various drainage classifications for the study watersheds.

Watershed	Very Poorly Drained	Poorly Drained	Somewhat Poorly Drained	Moderately Well Drained	Well Drained	Somewhat Excessively Drained	Excessively Drained
Maumee	48.7%	1.9%	33.0%	9.3%	7.0%	0.1%	0.1%
Portage	69.2	0.3	23.1	4.6	2.8	0.0	0.0
Sandusky (Bucyrus)	21.6	7.9	52.6	14.3	3.5	0.0	0.0
Broken Sword	14.7	8.4	51.7	20.4	4.7		
Sandusky (Upper Sandusky)	20.8	6.0	46.5	22.5	4.2		
Tymochtee	37.6	1.9	48.2	11.4	0.8		
Sandusky (Mexico)	23.7	5.7	47.7	19.5	3.5		
Honey Creek (Melmore)	11.7	13.8	64.4	7.6	2.5		
Wolf Creek (West)	43.5	13.2	39.8	0.5	3.0		
Wolf Creek (East)	15.7	16.9	65.4	0.9	1.1		
Sandusky (Fremont)	21.6	7.9	52.6	14.3	3.5	0.0	0.0
Huron	17.6	8.5	46.0	17.6	10.2	0.1	0.0

Table 6. Percentage distribution of soil erodibility as indicated by the K-value of soils in the study watersheds.

Watershed	K - Value									
	0.10	0.15	0.17	0.20	0.24	0.28	0.32	0.37	0.43	0.49
Maumee	1.4%	0.1%	2.8%	1.4%	17.5%	32.1%	2.1%	10.0%	32.4%	0.2%
Portage	0.0	0.0	6.5	2.7	7.9	57.0	2.6	6.1	17.0	0.0
Sandusky (Bucyrus)	0.0	0.0	0.0	0.8	12.3	5.6	10.5	35.8	35.0	0.0
Broken Sword	0.0	0.0	0.1	0.7	8.3	8.0	7.0	34.6	41.3	0.0
Sandusky (Upper Sandusky)	0.1	0.1	0.1	0.8	13.7	8.7	8.0	28.6	39.9	0.0
Tymochtee	0.2	0.5	0.4	0.0	23.6	13.7	0.9	12.0	48.6	0.0
Sandusky (Mexico)	0.3	0.3	0.3	0.4	15.8	9.5	4.9	24.7	44.0	0.0
Honey Creek (Melmore)	2.3	0.0	0.2	0.2	1.9	9.1	4.0	50.8	31.6	0.0
Wolf Creek (West)	0.0	0.0	0.2	0.2	1.6	44.7	1.9	16.7	34.8	0.0
Wolf Creek (East)	0.0	0.0	0.4	0.2	1.1	15.1	1.6	21.7	59.9	0.0
Sandusky (Fremont)	0.5	0.1	0.8	0.7	9.9	13.2	4.4	26.7	43.5	0.0
Huron	2.0	0.0	2.0	0.1	4.6	7.2	20.6	20.5	40.7	2.4

POTENTIAL GROSS EROSION

The LRIS system has been used as a base for calculating potential gross erosion in the Lake Erie watersheds (Urban et al. 1978). The universal soil loss equation (Wischmeier & Smith, 1978) was used to calculate gross erosion. The various components of the equation were estimated as follows (Urban et al., 1978):

- R factor data was taken from USLE Handbook 282 and developed on a county basis.
- K factors were taken from LRIS soils file by soil type.
- SL Slope percentage, S, was developed from LRIS soil phase data by taking the median value for slope range given. Slope length was estimated from local SCS experience and the recent 1% National Erosion Survey.
- C factors were developed from county-level estimates of crops grown; rotations were developed for each county based on local interpretation.
- P factor was assumed to be 1, i.e. there were no supporting conservation practices.

The gross erosion was calculated for each LRIS cell under current cropping practices. For each watershed, gross erosion was taken as the sum of the erosion from each cell within the watershed. A variety of scenarios were then incorporated into the calculations, such as the effect of no-till on suitable soils, minimum till, winter cover, and reduction of erosion to the soil loss tolerance factor. For each watershed and county, tabular summaries of the various scenarios as they apply to various soil management groups and land uses are presented in an appendix to the report of Urban et al. (1978).

A summary of the gross erosion data for the study watersheds is shown in Table 7. For each watershed the average potential gross erosion rate for cropland is listed, along with the cropland area and unit area erosion rate. For the cropland in each watershed the soils are divided into soil management groups with respect to their suitability for no-till crop production. For each group the percent of the cropland gross erosion, the percent of the cropland area and the unit area erosion rate is listed. Groups I and IV are well drained soils which are well suited for no-till crop production. Groups II and VII are suitable if underdrained by tile systems. Most such soils in the region are currently tiled. The remaining groups are considered unsuitable for no-till production. The bottom rows in Table 7 include vineyards, grassland and forests along with the cropland. The combined total gross erosion, area and unit area erosion for all of the above land uses are listed.

It can be seen from Table 7 that average potential gross erosion rates for cropland in the study watershed range from 4.5 to 10.8 metric tons per hectare per year. In each watershed the potential gross erosion rates are greatest in the soils which are most suitable for no-till (Groups I and IV) and next highest in the Groups II and VII soils which are also suitable for

Table 7. Summary of Gross Erosion Rates by Soil Management Groups for the Study Watersheds.

	Mauve	Portage	Huron River at Milan	Sandusky at Fremont	Sandusky at Mexico	Sandusky at Upper Sandusky	Sandusky at Bucyrus Creek	Dymochies Creek	Broken Wolf Sword	West Wolf East	Honey Creek at Melmore
Watershed Cropland											
Gross Erosion M.T./Yr.	8246849.4	478012.5	650768.8	1761999.9	1156798.7	533241.4	150615.2	248897.9	174830.9	56361.5	55913.6
Cropland (ha)	1050884.7	86248.8	71635.2	188343.3	108403.7	49215.9	16173.3	26838.5	16698.3	12553.3	9935.2
Erosion Rate M.T./ha/Yr	7.84	5.54	9.08	9.35	10.67	10.82	9.32	9.28	10.47	4.48	5.63
Soil Groups I & VI											
% Gross Erosion	36%	21%	45%	33%	40%	40%	38%	32%	42%	6%	5%
% Watershed Cropland	13%	6%	18%	15%	19%	21%	19%	10%	23%	3%	3%
Erosion Rate	21.09	18.67	21.99	21.09	22.57	20.39	18.22	30.75	18.71	8.18	8.09
Soil Groups II & VII											
% Gross Erosion	38%	50%	33%	46%	37%	38%	45%	39%	47%	60%	79%
% Watershed Cropland	32%	33%	38%	53%	46%	47%	53%	44%	52%	40%	63%
Erosion Rate M.T./ha/Yr	9.41	8.47	7.87	8.20	8.54	8.70	7.89	8.27	9.44	6.66	7.06
Other Groups											
% Gross Erosion	26%	29%	22%	21%	23%	22%	17%	29%	11%	34%	16%
% Watershed Cropland	55%	61%	44%	32%	35%	32%	28%	46%	25%	57%	34%
Erosion Rate M.T./ha/Yr	3.72	2.64	4.71	5.85	7.01	7.64	5.85	5.76	4.84	2.65	2.71
Watershed, Nonurban											
Gross Erosion M.T./Yr.	8279826.1	478959.7	655230.9	1769011.0	1161689.2	535602.5	151457.8	249550.9	175197.1	56428.2	56008.9
Cropland (ha)	1211552.8	95762.3	87334.2	214705.5	124008.2	57252.6	19332.4	29691.5	18651.4	13433.3	10967.2
Erosion Rate	6.84	5.00	7.51	8.25	9.37	9.35	7.84	8.40	9.39	4.19	5.11
											6.86

no-till. In general the soils which are unsuitable for no-till have low gross erosion rates. The effects of a variety of BMP's on the erosion from each soil management group for each watershed are shown in more detail in "Application of the Universal Soil Loss Equation in the Lake Erie Drainage Basin", Appendix I (Urban et al., 1978).

SECTION 5

STUDY METHODS

SAMPLE COLLECTION

Most of the samples upon which this report is based were collected at the USGS stream gages and/or chemical monitoring stations listed in Table 1. Each station is outfitted with a pumping system of the type used by the USGS for continuous monitoring of oxygen, temperature, conductivity, and pH. In a typical installation, two 4" diameter plastic pipes lead from the gage house to the stream. The longer, upstream pipe contains the inlet line(s) and the shorter down stream pipe contains the drain line(s). Both the inlet and drain lines are 1" diameter polyethylene and are wrapped with heat tape to prevent freezing in the winter. The end of the inlet pipe is located in that portion of the stream that flows year round (even during low flow conditions) and is ~10 cm off the stream bed. A stainless steel inlet screen (18" long 1/4" diameter holes) prevents larger debris from clogging the inlet pipe. The inlet line extends to the end of this screen.

The stations are equipped with a continuously operating pumping system (Continental, model EC448, progressive cavity screw pump) with an output of about 8 gallons per minute. The output of the pump leads into a reservoir designed to drain completely should the pump fail. This prevents repeated sampling of "dead" water.

Automatic samplers (ISCO model 1680 or equivalent) are used to collect discreet samples at preset intervals of time from the reservoir of the continuous pumping system. These samplers are capable of sampling at intervals ranging from 1 to 999 minutes. Under non-event conditions the samplers are set to take four 450 ml samples per day at 1:00, 7:00, 13:00 and 19:00 hours. For the smaller watersheds during storm events the sampling frequency is increased to 8 to 12 samples per day. To avoid sample contamination the samplers reverse pumping before and after each sample is taken. The samplers are run on batteries which are "trickle charged" from the electric power at the station. Thus power outages do not cause the timer to fail and sampling will resume on schedule with the proper sample bottle in place when the current comes back on and the pump resumes operation.

The sampler bases have room for 28 high density polyethylene bottles. Sample identification is based on sets of 28 bottles. The bottles are numbered from one to 28 and each set has a letter code. The cleaning procedure for the nutrient bottles includes a hot tap water wash with brushing to remove any sediment. This is followed with two rinses with hot tap water and air drying before use. The caps go through the same washing procedure.

The sampling stations are visited weekly except for the smaller watersheds which, during runoff events, are visited more often. The 28 bottles in the base allow 4 collections per day for a seven-day period. The normal schedule for visiting the stations involves changing the sampler bases on Mondays or Tuesdays so that sample analyses can be completed by Thursdays and the sample bottles cleaned and prepared for the collection routes on the following Mondays and Tuesdays.

While at the sampling station, the field technicians collect several extra samples as part of the quality control program. Three replicate samples are collected from the pumping system. One of these is placed in the sampler base for the following week's collection. This stored sample is used to monitor the effects of one week of storage at ambient temperatures within the sampler bases. Thermostated heaters prevent the gage house temperatures from dropping below 3 degrees Centigrade in the winter period. The other two pumped samples are returned to the laboratory on the day of collection. Both are analyzed and the resulting data used for determining laboratory precision, and for comparison with the sample which has been stored and analyzed the following week. Periodically the field technicians also collect grab samples from a bridge near the sampling station for comparison with the pumped samples. The results of these quality control procedures are presented later in this section of the report.

The field technicians also check the operation of the stage recording equipment and compare the bubble gage reading with a nearby wire weight gage. The pump operation is checked and the inlet screens cleaned if necessary. The sampler timers are checked and adjusted.

SAMPLE PRESERVATION AND STORAGE

No preservatives are used in the sample bottles. The samplers remain in the sampler bases at ambient gage house temperatures as they are collected. The "age" of the samples at the time they are delivered to the laboratory ranges from 7 days to 4 hours. Within 48 hours of delivery to the lab, all samples are filtered through prerinsed 0.45 micron membrane filters and transferred to autoanalyzer tubes. Analyses of both soluble and total nutrients are completed within three days of delivery to the laboratory.

For studies of this type, it would be impractical to attempt to meet the preservation and storage requirements for soluble nutrients, such as soluble reactive phosphorus, nitrates and ammonia. Instead our approach has been to document the extent and direction of change during sample storage and to take these effects into account when interpreting the data. The results of our studies of storage effects are presented in the quality control section.

LABORATORY PROCEDURES

Selection of Samples for Analysis

The automatic samplers operate continuously and collect a minimum of 4 samples per day. All of the samples are returned to the laboratory each week. If a runoff event was in progress at the sampling station, as evidenced by either a high flow or high turbidity, all of the samples are analyzed. If runoff events were not occurring at the station, one sample per day is analyzed and the remainder are discarded. Thus, data are collected on both high and low-flow conditions but the frequency of analyses is much greater for high-flow samples.

Sample Handling

Figure 6 is a summary flow chart showing the groupings of analyses performed on the samples. Not all analyses are performed on each sample.

Analytical Methods

The analytical methods used in the laboratory are summarized in Appendix 1. More detailed descriptions of the methods are contained within the laboratory's Handbook on Quality Assurance.

QUALITY CONTROL

Precision

The precision associated with the sampling and analysis program described above can be judged from the analyses of replicate pumped samples. These data are summarized in Table 8, which includes data collected during the 1978 water year. The number of replicate pairs in the data set for each parameter is listed. Since the precision calculations are used for establishing control limits, the indicated number of pairs with the largest differences were deleted from each data set. In general less than 5% of the pairs were rejected. The mean difference between the replicates is shown for each parameter. Dividing the mean difference by 1.128 provides an estimate of the precision (ASTM, 1976). To indicate the relationship between the precision and the range of environmental values, the mean of the 5th percentile concentration for the Maumee, Fremont and Melmore stations is listed as is the mean of the 95th percentile. These values were obtained from concentration exceedency tables for each station. The ratio of the 90% inclusive range (ie. 5% to 95%) to the precision indicates that the precision is very good in relation to the range of values encountered in environmental samples.

The r-squared values (coefficient of determination) also shows the close agreement between the replicate pairs.

Effects of Sample Storage

In Table 9, the effects of one week of sample storage on analytical values are shown. The data were analyzed using the paired T-test procedure contained within SPSS (Statistical Package for the Social Sciences). For each parameter except suspended solids, changes did occur during storage that were, from a statistical standpoint, highly significant. The means of the fresh and stored values are shown along with the mean differences, correlations, T-values, and associated probabilities.

The extent of change during storage is summarized in Table 10. The largest changes occur in soluble reactive phosphorus where the average change was a 10.4% increase. For this parameter the pairs were broken down into various ranges of fresh SRP concentrations as well as suspended solids and conductivity ranges. The largest changes (+78.8%) occurred when the fresh SRP values were less than 0.050 mg/l. Low SRP values often occur when algal

Figure 6.

FLOW CHART FOR SAMPLE ANALYSES

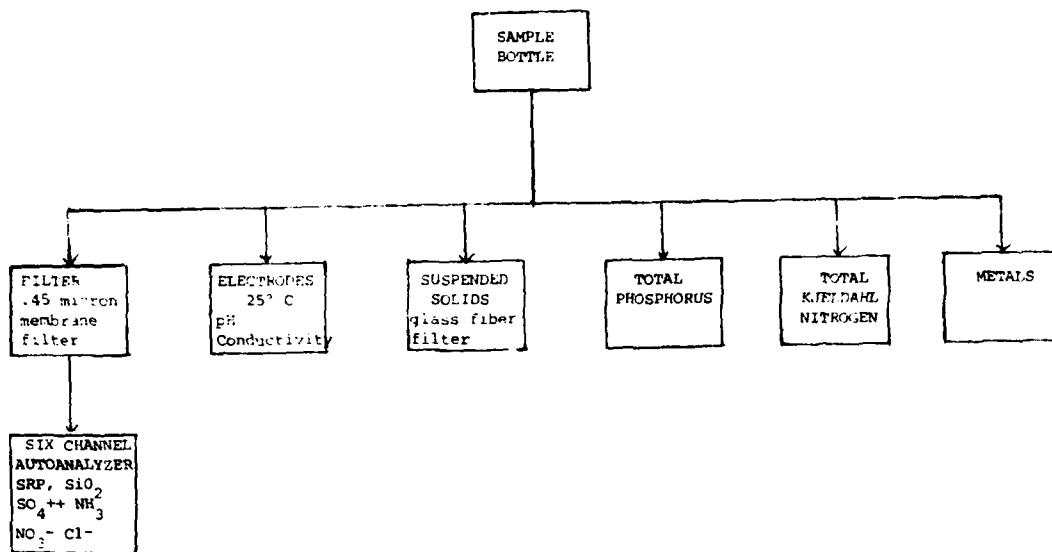


Table 8. Precision Data based on analysis of replicate pumped samples.

Parameter	Pairs N	Deleted Values	Mean Difference mg/l	Precision mg/l	R ²	Environmental Range* 5 th percentile 95 th percentile mg/l		90% Range Precision (ratio)
Soluble Reactive Phosphorus	292	15	.0066	.0058	.992	.020	.187	25
Total Phosphorus	301	12	.0108	.0096	.993	.099	.580	50
Nitrate/Nitrite - N	305	14	.0708	.0628	.997	.397	9.087	138
Ammonia - N	304	14	.0407	.0360	.966	.020	.824	22
Suspended Solids	305	14	4.49	3.98	.994	4.38	264.3	58
Conductivity (umhos)	319	14	11.25	9.92	.989	367.7	960.0	60

*Based on the mean 5th percentile concentrations for the Maumee, Fremont and Melmore stations and mean 95th percentile concentrations.

Table 9. The effects of one week of sample storage on analytical values.

STATISTICAL PACKAGE FOR THE SOCIAL SCIENCES

FILE RIVER1 (CREATION DATE = 02/27/81)

16:30:17 02/27/81

T - T E S T									
VARIABLE	NUMBER OF CASES	MEAN	STANDARD DEVIATION	STANDARD ERROR	(DIFFERENCE) MEAN DEVIATION	STANDARD ERROR	2-TAIL CORR. PROB.	T VALUE	DEGREES OF FREEDOM
FRSHSRP	711	0.1055	0.132	0.005	-0.0110	0.030	0.975	-9.87	710
STORSRP		0.1165	0.133	0.005					
FRSHTP	762	0.2380	0.208	0.008	0.0033	0.024	0.993	3.79	761
STORTP		0.2346	0.207	0.007					
FRSHN023	775	3.2145	2.769	0.099	-0.0700	0.454	0.986	-4.29	774
STORN023		3.2046	2.729	0.098					
FRSHN03	761	0.2497	0.373	0.014	0.0172	0.109	0.959	4.37	760
STORN03		0.2325	0.383	0.014					
FRSHS	777	46.8099	99.109	3.556	0.3955	16.527	0.986	0.67	776
STORS		46.4144	99.583	3.573					
FRSHCOND	766	719.2715	232.236	8.391	-3.0653	20.979	0.996	-4.04	765
STORCOND		722.3368	231.415	8.361					

Table 10. Average Change in Concentration during one week of sample storage.

Parameter	N	Mean Fresh mg/l	Mean Stored mg/l	% Change in Fresh
SRP				
all values	711	0.1055	0.1165	10.4%
SRP < 0.050	226	0.0260	0.0465	78.8%
0.050 < SRP < 0.100	232	0.0730	0.0815	+ 11.6%
SRP > 0.100	242	0.2127	0.2172	+ 2.1%
SRP if SS < 50	540	0.1089	0.1189	+ 9.2%
SRP if SS > 50	171	0.0948	0.1089	+ 14.9%
SRP if Cond. < 500	107	0.0942	0.0967	+ 2.7%
SRP if Cond. > 500	604	0.1075	0.1200	11.6%
TP	762	0.2380	0.2346	- 1.9%
NO ₃ - NO ₂	775	3.2145	3.2846	+ 2.2%
NH ₃	761	.2497	.2325	- 6.9%
SS	777	46.810	46.414	- 0.8%
Conductivity	766	719.27	722.34	+ 0.4%

densities are high. It is possible that during one week of storage in the dark, release of soluble phosphorus could occur. Samples with fresh SRP values greater than 0.10 mg/l increased by only 2.1% during storage. At 8 of the 12 transport stations the flux weighted mean concentration exceeded 0.10 mg/l (see Table 26).

The increase in SRP concentrations during storage was higher (+14.9%) for samples with suspended solids greater than 50 mg/l than for samples with suspended solids less than 50 mg/l (9.2%). Samples with conductivities less than 500 umhos showed the smallest increase with storage (2.7%). Since low conductivities correlate with high flows, under conditions of high transport the SRP values did not show much increase. This has been confirmed by calculations of the effects of storage on flow weighted mean concentrations of SRP. For all the stations, storage for one week increased the SRP values by 1.2%, with individual stations ranging from +13.1% to -7.9%.

For total phosphorus, nitrate, suspended solids and conductivity, the mean changes during storage were -1.9%, +2.2%, -0.8% and +0.4% respectively. These changes would have little effect on loading calculations since errors in flow measurement are likely to exceed errors introduced by storage effects of this size. Ammonia does show a larger effect of sample storage (6.9%) but ammonia nitrogen transport is much less important than nitrate nitrogen transport.

The paired T-test data described above were based on paired samples collected through the 1978 water year. Paired T-tests run on samples collected in 1979 and 1980 gave very similar results.

It should be noted that the storage effects discussed above reflect sample storage for a period of 1 week. The average time of sample storage for environmental samples is about 4 days. Consequently we view the changes in sample concentration during storage to be insignificant with respect to loading calculations. The critical factor for loading calculations is to have large numbers of samples during high flow periods. To meet the sample storage and preservation requirements for soluble nutrients, as specified in the EPA Procedures Manual (EPA 1979), would so increase the sampling costs that many fewer samples could be collected and analyzed and consequently loading estimates would become less precise.

Comparison of Pumped and Grab Samples

In Table 11, data on pumped and grab samples are presented. Paired T-tests indicate that there is no significant differences between the pumped and grab samples. The correlations between the pumped and grab samples are also very good. The close agreement between the pumped and grab samples for suspended solids and for total phosphorus reflects the fact that in these rivers the suspended solids transport is dominated by clay and silt sized particles. Particle size analyses by the USGS in these rivers indicate that over 82% of the suspended solids by weight is clay (<0.004 mm) and 15% is silt ($0.004 - 0.062$ mm) (Antilla & Tobin, 1978). Consequently, the use of depth integrated samples is not necessary for accurate suspended solids measurements.

FLOW DATA

All flow data are obtained from the USGS. Copies of the "Primary Computation of Gage Heights and Discharge" are obtained for each station soon after the gage house tapes are processed. These printouts include the stage measurements at hourly intervals for each day. From these tables the gage height at the time of sample collection is obtained and entered into the data set for that sample.

For each station expanded rating tables are obtained from the USGS. These rating tables are stored in the computer and a computer program then generates the flow values at times of sample collection using the gage height and the rating table.

DATA STORAGE

Table 12 is a sample printout of the archive files. The printout includes information for samples collected at the Melmore gaging station between 1900 hours April 7, 1979 and 0100 hours April 17, 1979. The year, month, day and time of sample collection are shown in the first two columns. All data are stored in a time sequence for a given station. The day of the water year is shown in the next column. It is used as a time base for several of the plot programs. The stage data, in feet, are shown in the next column. The flow in CFS is generated by a program that refers to a rating table supplied by the USGS. The flow table lists flows for each tenth of a foot increment in stage. Our computer program does a linear interpolation to

Table 11. Paired T-test comparisons of pumped and grab samples.

STATISTICAL PACKAGE FOR THE SOCIAL SCIENCES

FILE GFFAIP2 (CREATION DATE = 03/17/81)

T - T E S T										
VARIABLE	COUNT OF CASES	MEAN	STANDARD DEVIATION	STANDARD ERROR	(DIFFERENCE) MEAN DEVIATION	STANDARD ERROR	2-TAIL CCF. P-VALUE	T-VALUE	DEGREE OF FREEDOM	T-TEST
GRABSP	236	0.0815	0.096	0.006	-0.0005	0.041	0.003	0.976	0.000	237
PUMPSP		0.0820	0.096	0.006						
GRABTP	229	0.2074	0.162	0.011	-0.0038	0.074	0.005	0.902	0.000	228
PUMPTP		0.2112	0.170	0.011						
GRABN23	242	2.7586	3.261	0.210	-0.0138	0.358	0.023	0.994	0.000	241
PUMPN23		2.7724	3.242	0.215						
GRABNH3	239	0.1190	0.190	0.012	-0.0142	0.209	0.014	0.486	0.000	238
PUMPNH3		0.1332	0.219	0.014						
GRABSS	239	57.4675	127.197	8.228	-5.8869	66.395	4.295	0.891	0.000	238
PUMPSS		62.3544	146.268	9.461						

Table 12. Sample Archive Printout for Transport Stations.

PAGE 1	TIME	26-FEB-81	09:44:52	MLM79	HT	OP	TP	SS	NO.3	NH3	COND	TEMP	FH	SI02	CL	TN	TOC	CA	MG	K	MA	FE	CU	MN
Y0407	1900	188.792	3.96	304.88	24	.033	.207	67.1	6.57	.108	451	-1	7.79	7.11	-1	1.48	-1	-1	-1	-1	-1	-1	-1	-1
Y0408	1900	189.792	3.63	233.97	21	.031	.158	46	7.43	.197	491	-1	7.88	6.62	-1	.97	-1	-1	-1	-1	-1	-1	-1	-1
Y0409	1900	190.542	5.94	930.64	12	.075	.384	204	5.35	.224	346	-1	7.71	6.06	-1	1.87	-1	-1	-1	-1	-1	-1	-1	-1
Y0410	1900	191.292	6.11	1002.8	9	.069	.32	137	5.94	.110	334	-1	7.38	8.13	-1	1.69	-1	-1	-1	-1	-1	-1	-1	-1
Y0411	1900	191.792	5.17	1029.6	12	.06	.246	131	6.65	.206	333	-1	7.49	6.62	-1	1.75	-1	-1	-1	-1	-1	-1	-1	-1
Y0412	1900	192.292	5.94	930.64	12	.062	.246	87.3	7.45	.121	345	-1	7.58	8.4	-1	1.77	-1	-1	-1	-1	-1	-1	-1	-1
Y0413	1900	192.792	5.28	679.26	12	.059	.186	70.3	7.68	.091	380	-1	7.65	8.42	-1	1.26	-1	-1	-1	-1	-1	-1	-1	-1
Y0414	1900	192.792	4.6	462.3	12	.052	.144	50.6	7.38	.109	416	-1	7.75	9.01	-1	.96	-1	-1	-1	-1	-1	-1	-1	-1
Y0415	1900	193.292	4.21	362.23	12	.042	.142	41	6.9	.081	442	-1	7.52	8.6	-1	1.3	-1	-1	-1	-1	-1	-1	-1	-1
Y0416	1900	193.292	4.03	320.41	12	.04	.106	39.1	6.64	.304	463	-1	7.91	9.73	-1	.88	-1	-1	-1	-1	-1	-1	-1	-1
Y0417	1900	193.792	3.89	289.67	12	.052	.09	39.5	6.58	.115	484	-1	8	7.87	-1	.85	-1	-1	-1	-1	-1	-1	-1	-1
Y0418	1900	194.292	4.72	496.04	9	.069	.538	323	5.13	.161	400	-1	7.73	6.03	-1	1.93	-1	-1	-1	-1	-1	-1	-1	-1
Y0419	1900	194.792	8.62	2405.8	6	.067	1.31	982	2.7	.164	200	-1	7.54	5.59	-1	4.58	-1	-1	-1	-1	-1	-1	-1	-1
Y0420	1900	195.042	8.62	3302.4	4	.07	1.46	1061	2.72	.109	188	-1	7.43	4.74	-1	5.35	-1	-1	-1	-1	-1	-1	-1	-1
Y0421	1900	195.292	9.82	3702.8	3	.057	1.56	676	2.59	.149	186	-1	7.34	4.38	-1	6.66	-1	-1	-1	-1	-1	-1	-1	-1
Y0422	1900	195.542	10.37	3786.1	3	.056	1.54	1098	2.5	.19	178	-1	7.34	4.36	-1	5.9	-1	-1	-1	-1	-1	-1	-1	-1
Y0423	1900	195.667	10.26	3684.6	3	.044	1.58	780	2.39	.066	171	-1	7.31	5.78	-1	5.98	-1	-1	-1	-1	-1	-1	-1	-1
Y0424	1900	195.792	10.01	3458.9	4	.045	1.49	944	2.58	.188	174	-1	7.27	4.67	-1	6.09	-1	-1	-1	-1	-1	-1	-1	-1
Y0425	1900	196.042	9.47	3024.9	4	.041	1.56	961	2.52	.101	173	-1	7.3	4.69	-1	5.61	-1	-1	-1	-1	-1	-1	-1	-1
Y0426	1900	196.167	9.26	2865	3	.036	1.52	1008	2.57	.156	169	-1	7.32	5.04	-1	6.15	-1	-1	-1	-1	-1	-1	-1	-1
Y0427	1900	196.292	9.06	2716.8	3	.043	1.42	884	2.68	.32	173	-1	7.36	5.03	-1	5.57	-1	-1	-1	-1	-1	-1	-1	-1
Y0428	1900	196.417	8.84	2559	3	.025	1.38	760	2.78	.899	181	-1	7.36	6.53	-1	5.07	-1	-1	-1	-1	-1	-1	-1	-1
Y0429	1900	196.542	8.6	2392	3	.036	1.24	645	2.79	.048	191	-1	7.42	6.46	-1	4.75	-1	-1	-1	-1	-1	-1	-1	-1
Y0430	1900	196.667	8.36	2232	3	.032	1.14	496	3.41	.215	208	-1	7.71	7.59	-1	3.7	-1	-1	-1	-1	-1	-1	-1	-1
Y0431	1900	196.792	8.13	2086.6	3	.018	1.07	446	3.57	.114	212	-1	7.55	9.82	-1	3.33	-1	-1	-1	-1	-1	-1	-1	-1
Y0432	1900	196.917	7.89	1940.1	3	.015	1.01	405	3.52	.078	193	-1	7.33	9.27	-1	3.47	-1	-1	-1	-1	-1	-1	-1	-1
Y0433	1900	197.042	7.67	1810.9	3	.03	.976	358	3.59	.072	321	-1	7.26	7.5	-1	2.93	-1	-1	-1	-1	-1	-1	-1	-1
Y0434	1900	197.167	7.44	1679.2	3	.028	.912	329	3.68	.09	216	-1	7.38	7.2	-1	3.14	-1	-1	-1	-1	-1	-1	-1	-1
Y0435	1900	197.292	7.18	1532	3	.023	.904	300	3.74	.123	224	-1	7.44	7.27	-1	3.08	-1	-1	-1	-1	-1	-1	-1	-1
Y0436	1900	197.417	6.94	1402.2	3	.045	.928	273	3.71	.219	233	-1	7.47	7.9	-1	8.23	-1	-1	-1	-1	-1	-1	-1	-1
Y0437	1900	197.542	6.69	1274.1	3	.034	.792	257	3.86	.1	239	-1	7.51	7.98	-1	2.86	-1	-1	-1	-1	-1	-1	-1	-1
Y0438	1900	197.667	6.46	1162.2	3	.029	.784	247	3.93	.098	246	-1	7.5	9.86	-1	3.29	-1	-1	-1	-1	-1	-1	-1	-1
Y0439	1900	197.792	6.26	1070	3	.019	.768	247	4.03	.058	252	-1	7.53	11.1	-1	3.15	-1	-1	-1	-1	-1	-1	-1	-1
Y0440	1900	197.917	6.06	981.16	3	.029	.73	235	4	.159	258	-1	7.54	9.05	-1	2.66	-1	-1	-1	-1	-1	-1	-1	-1
Y0441	1900	198.042	5.89	910.2	3	.03	.71	330	4.03	.067	263	-1	7.54	9.05	-1	2.66	-1	-1	-1	-1	-1	-1	-1	-1

END OF MLM79 26-FEB-81 SAMPLE ARCHIVE PRINT OUT

generate the flow for the hundredth place in the stage data.

The column labeled MT contains a time multiplier in hours. The time multiplier is obtained by a program which, for a given sample, calculates the time interval between the preceeding sample and the following sample. This time is divided by 2, to give the duration of time for which that sample is used to characterize the stream transport. If the calculated multiplier exceeds 24 hours the multiplier is set equal to 24 hours so that no single sample is used to characterize the river for more than a 24 hour period. The sample archive printout illustrates that during periods of high flow, more samples are analyzed and consequently the time multipliers are smaller. The time multipliers are used in the programs for calculating material flux, total flow, and time exceedency tables.

The concentrations of dissolved reactive phosphorus (OP), total phosphorus (TP), suspended solids (SS), nitrate + nitrite nitrogen (NO₂+N), ammonia nitrogen (NH₃), conductivity in umhos at 25 degrees C (cond.), pH, SiO₂, chloride, Total Kjeldahl Nitrogen (TKN) and metals are listed in the remaining columns. All concentrations are in the units of mg/l for the element (ie. as P or N) with the exception of silica which is reported as SiO₂. A minus one (-1) is used to indicate that the sample was not analyzed for that parameter.

Following data entry into the laboratory's PDP 11 computer system, a preliminary archive printout is obtained for use in data verification. The values are compared with the laboratory bench sheets. Corrections are made as necessary and the archives files are transferred to the college's main computer system, a PRIME 550.

All of the data collected at the transport stations have been transferred to the STORET system. A program has been written that directly generates the format for STORET files and tapes.

COMPUTATIONAL METHODS

A variety of computer programs for the PRIME 550 have been written for conducting routine calculations on the data sets. These include programs to calculate flux, annual loading using flow duration tables and exceedency tables. Examples of the outputs of these programs are presented below, along with explanations of the way in which the calculations are done.

Flux Calculations

Table 13 is an example of the summary table from a flux calculation. The program allows the selection of the river station, the beginning and ending dates and times, and the parameter. The total load in metric tons and short tons over the time interval are then listed. The total load is the sum of the loads of the individual samples collected during the time interval. This is illustrated in Table 14 which is an optional printout for the flux summaries. For each sample the load is calculated as:

Table 13. Sample Printout of Program for Flux Calculations.

FLUX SUMMARY FOR THE MELMORE RIVER
 BETWEEN THE DATES 790407 AND 790417
 FOR THE PARAMETER TP
 TOTAL LOAD METRIC TONS 25.88192 SHORT TONS 28.52187
 TOTAL VOLUME CUBIC METERS 2.6856644E 07 CFS-DAYS 10989.74
 MEAN FLOW (M**3/SEC) 31.67804 1119.365
 MONITORED TIME (HRS) 235.5000
 MEAN CONCENTRATION (MG/L) 0.8446275
 FLUX WEIGHTED MEAN CONC. (MG/L) 0.9637064
 INSTANTANEOUS FLOW WT. MEAN CONC. (MG/L) 1.164046
 TIME WEIGHTED AVERAGE CONC. (MG/L) 0.5357952
 NUMBER OF SAMPLES 35

Table 14. Sample printout of flux summary option which includes data for individual samples and cumulative totals.

SAMPLE	DATE	TIME	TP (MG/L)	FLOW (CFS)	MT (HRS)	TOTAL LOAD (MT)	TOTAL FLOW (M**3)	TOTAL TIME (HRS)
1	790407	1900	2.0700E-01	304.9	24.0	1.5431E-01	7.4547E 05	2.4000E 01
2	790408	1900	1.5800E-01	234.0	21.0	2.3340E-01	1.2460E 06	4.5000E 01
3	790409	1300	3.8400E-01	930.6	12.0	6.7030E-01	2.3838E 06	5.7000E 01
4	790409	1900	3.2000E-01	1003.0	9.0	9.6456E-01	3.3033E 06	6.6000E 01
5	790410	0700	3.0600E-01	1030.0	12.0	1.3497E 00	4.5621E 06	7.8000E 01
6	790410	1900	2.4600E-01	930.6	12.0	1.6296E 00	5.6999E 06	9.0000E 01
7	790411	0700	1.8600E-01	679.3	12.0	1.7841E 00	6.5303E 06	1.0200E 02
8	790411	1900	1.4400E-01	462.3	12.0	1.8655E 00	7.0955E 06	1.1400E 02
9	790412	0700	1.4200E-01	352.2	12.0	1.9284E 00	7.5384E 06	1.2600E 02
10	790412	1900	1.0600E-01	320.4	12.0	1.9699E 00	7.9381E 06	1.3800E 02
11	790413	0700	9.0000E-02	289.7	12.0	2.0018E 00	8.2842E 06	1.5000E 02
12	790413	1900	5.3800E-01	496.3	9.0	2.2464E 00	8.7390E 06	1.5900E 02
13	790414	0100	1.3140E 00	2406.0	6.0	4.1788E 00	1.0210E 07	1.6500E 02
14	790414	0700	1.4660E 00	3302.0	4.5	6.3984E 00	1.1724E 07	1.6950E 02
15	790414	1000	1.5640E 00	3703.0	3.0	8.1684E 00	1.2855E 07	1.7230E 02
16	790414	1300	1.5430E 00	3786.0	3.0	9.9539E 00	1.4013E 07	1.7550E 02
17	790414	1600	1.5820E 00	3685.0	3.0	1.1736E 01	1.5139E 07	1.7850E 02
18	790414	1900	1.4900E 00	3459.0	4.5	1.4098E 01	1.5724E 07	1.8300E 02
19	790415	0100	1.5620E 00	3025.0	4.5	1.5264E 01	1.8111E 07	1.8750E 02
20	790415	0400	1.5200E 00	2865.0	3.0	1.7595E 01	1.8987E 07	1.9050E 02
21	790415	0700	1.4240E 00	2717.0	3.0	1.8778E 01	1.9817E 07	1.9350E 02
22	790415	1000	1.3840E 00	2559.0	3.0	1.9860E 01	2.0599E 07	1.9650E 02
23	790415	1300	1.2480E 00	2392.0	3.0	2.0773E 01	2.1330E 07	1.9950E 02
24	790415	1600	1.1480E 00	2232.0	3.0	2.1556E 01	2.2013E 07	2.0250E 02
25	790415	1900	1.0760E 00	2087.0	3.0	2.2242E 01	2.2650E 07	2.0550E 02
26	790416	2200	1.0100E 00	1940.0	3.0	2.2841E 01	2.3243E 07	2.0850E 02
27	790416	0100	9.7600E-01	1811.0	3.0	2.3381E 01	2.3797E 07	2.1150E 02
28	790416	0400	9.1200E-01	1679.0	3.0	2.3849E 01	2.4310E 07	2.1450E 02
29	790416	0700	9.0400E-01	1532.0	3.0	2.4273E 01	2.4778E 07	2.1750E 02
30	790416	1000	8.2800E-01	1402.0	3.0	2.4627E 01	2.5207E 07	2.2050E 02
31	790416	1300	7.9200E-01	1274.0	3.0	2.4936E 01	2.5596E 07	2.2350E 02
32	790416	1600	7.8400E-01	1162.0	3.0	2.5214E 01	2.5952E 07	2.2650E 02
33	790416	1900	7.6800E-01	1070.0	3.0	2.5465E 01	2.6279E 07	2.2950E 02
34	790416	2200	7.3000E-01	981.2	3.0	2.5684E 01	2.6578E 07	2.3250E 02
35	790417	0100	7.1000E-01	910.2	3.0	2.5882E 01	2.6857E 07	2.3550E 02

$$\text{mg/l} \times \text{CFS} \times \text{hours} \times 1.018810 \times 10^{-4} = \text{metric tons}$$

Also the flow volume is calculated as:

$$\text{CFS} \times \text{hours} \times 101.88 = \text{cubic meters}$$

In the optional printout (Table 14) the cumulative total load, cumulative flow and cumulative time are reported for each successive sample collected during the time interval. The cumulative values for the final sample are reported in the summary tables. This method of flux calculation is equivalent to the midinterval method which the USGS uses to calculate sediment loads at daily sediment stations (Porterfield, 1972). The various time multipliers are the equivalent of subdivided days in the USGS calculations.

The flux summary tables also list the total volume of water monitored during the time interval, both in cubic meters and CFS-days. The mean flow during the time interval is calculated by dividing the total volume of water by the monitored time. The mean flow is listed both in cubic meters per second and cubic feet per second. The total monitored time in hours is also listed in the summary. By listing the monitored time, the extent of gaps in the monitoring record over the time interval can be determined.

The flux summary includes 4 calculations of concentration during the time interval. These are calculated as follows:

$$\text{Mean Concentration} = \frac{\sum c_i}{N} \quad (1)$$

$$\text{Flux Weighted Mean Concentration} = \frac{\sum c_i t_i q_i}{\sum t_i q_i} = \frac{\text{Total Flux}}{\text{Total Flow}} \quad (2)$$

$$\text{Instantaneous Flow Wt. Mean Concentration} = \frac{\sum c_i q_i}{\sum q_i} \quad (3)$$

$$\text{Time Weighted Average Concentration} = \frac{\sum c_i t_i}{\sum t_i} \quad (4)$$

Where C_i = concentration of i th sample
 t_i = time multiplier of the sample
 Q_i = instantaneous flow for i th sample
 N = number of samples

The interpretation of these various types of average concentrations is described in the next section. The flux summary also lists the total number of samples collected during the time interval.

Our flux calculation programs include a number of convenient options. Flux calculations can be obtained for any of the chemical parameters. In specifying the dates, the flux for individual storms, months, water years or the entire period of record can be selected. One option selects all of the samples for a specified month within a specified period of years. Table 15 is a summary printout for all of the samples collected during the month of April during the period of record.

Another option useful when calculating fluxes over a long period of time includes, along with the summary table, a listing of the 50 largest flow volumes (discharge X time multiplier) for individual samples. The dates of the samples, concentrations and flows along with percent of the total flux accounted for by each sample is listed. Similar information is also listed for the 50 largest fluxes. These lists are useful for screening and verifying those samples which are major contributors to the calculations of weighted average concentrations. Examples of these outputs as applied to a flux calculation of Total Phosphorus at the Melmore station during the 1979 water year are shown in Tables 16, 17, 18. This type of screening has been done for all of the flux weighted mean concentraions reported in the next section.

Exceedency Calculations

A second set of program deals with calculations of the percent of time given concentrations, flows or fluxes are exceeded. In addition the program calculates the percent of the total load accounted for by concentrations, flows or fluxes up through each sample in the exceedency ranking. Tables 19, 20 and 21 provide examples of concentration, flow and flux exceedency tables for the same sample data set from the Melmore station as shown in the sample archive printout (Table 12).

The programs first allow selection of: the type of exceedency table (ie concentration, flow or flux); the stations; the initial and final dates and times; and the parameter. In the case of a concentration exceedency table, (see Table 19) all of the samples are sorted into a sequence of increasing concentrations. The printout includes the date, the time multiplier, the instantaneous flow in CFS and the instantaneous flux in kg/hr for each sample. The time multipliers are sequentially added giving a cumulative sum-of-time. For each sample the current sum-of-time is expressed as a percentage of the total time. The total time is the sum-of-time for the sample with the highest concentration. Although the percentage is labeled "Percent Exceedency" it is actually the percent of time that the concentration is less than the sample concentration in the ranking. The actual "Percent Exceedency" is 100 minus the listed Percent Exceedency.

The relationship between concentration exceedency and total loading is shown in the final two columns of the printout. For each sample the total load (ie the product of the time multiplier and the instantaneous flux) is calculated and sequentially added, producing the column labeled sum-of-flux. For each sample, the sum-of-flux is expressed as a percentage of the total flux. Although these percentages are also labeled "Percent Exceedency", they actually show the percent of the total flux accounted for by that sample plus all of the samples with lower concentrations.

In the case of flow exceedency tables (Table 20), samples are ranked in order of increasing flow. The column labeled "Percent Exceedency" and adjacent to the sum-of-time column shows the percentage of time that flows are less than the sample flow. The listed "Percent Exceedency" should be subtracted from 100 to obtain the actual percent of time the flows exceed the listed flow for that sample. The relationships between flow exceedency and total transport are shown in the final 2 columns of the flow exceedency printout. The sum-of-flux and the "Percent Exceedency" are calculated in the

Table 15. Sample printout of flux summary option for selected months.

```

MONTHLY FLUX SUMMARY FOR THE MELMORE RIVER
IN THE APRILS OF 76 THROUGH 79
FOR THE PARAMETER TP
TOTAL LOAD METRIC TONS 42.38480 SHORT TONS 46.70805
TOTAL VOLUME CUBIC METERS 7.7128112E 07 CFS-DAYS 31560.82
MEAN FLOW (M**3/SEC) 8.252888 291.6215
MONITORED TIME (HRS) 2595.998
MEAN CONCENTRATION (MG/L) 0.3640593
FLUX WEIGHTED MEAN CONC. (MG/L) 0.5495377
INSTANTANEOUS FLOW WT. MEAN CONC. (MG/L) 0.7623307
TIME WEIGHTED AVERAGE CONC. (MG/L) 0.2073411
NUMBER OF SAMPLES 223

```

Table 16. Sample printout of the flux summary for the 1979 water year loading of total phosphorus at the Melmore gaging station.

```

FLUX SUMMARY FOR THE MELMORE RIVER
BETWEEN THE DATES 781001 AND 790923
FOR THE PARAMETER TP
TOTAL LOAD METRIC TONS 82.99326 SHORT TONS 91.45856
TOTAL VOLUME CUBIC METERS 1.5828461E 08 CFS-DAYS 64770.05
MEAN FLOW (M**3/SEC) 6.263243 221.3160
MONITORED TIME (HRS) 7019.997
MEAN CONCENTRATION (MG/L) 0.3826081
FLUX WEIGHTED MEAN CONC. (MG/L) 0.5243292
INSTANTANEOUS FLOW WT. MEAN CONC. (MG/L) 0.6503026
TIME WEIGHTED AVERAGE CONC. (MG/L) 0.2638122
NUMBER OF SAMPLES 570

```

Table 17. Sample printout showing the 50 largest flow volumes contributing to the phosphorus loading at Melmore during the 1979 water year.

DATE	TIME	WT	FLOW	TP	FLOW VOL	X VOL	FLUX	X FLUX
790306	1900	15.00	30.92	0.21200	463.81	1.055	0.35398	0.427
790307	1900	24.00	18.92	0.18800	454.18	1.033	0.30739	0.370
790414	1900	4.50	97.89	1.4900	440.49	1.002	2.3626	0.847
790414	700	4.50	93.46	1.4660	420.56	0.957	2.2195	0.674
790414	100	6.00	68.08	1.3140	408.50	0.929	1.9324	0.328
790415	100	4.50	85.60	1.5620	385.22	0.876	2.1662	0.611
790224	700	6.00	63.90	0.56700	383.41	0.872	0.78261	0.943
790526	1000	13.50	27.77	0.46300	374.85	0.853	0.62480	0.753
790405	1900	21.00	17.84	0.32700	374.72	0.852	0.44112	0.532
790310	1900	24.00	15.52	0.17000	372.38	0.847	0.22790	0.277
790224	100	6.00	61.17	0.58500	367.02	0.835	0.77427	0.933
790305	1900	6.00	59.58	0.29900	357.46	0.813	0.38477	0.464
790410	700	12.00	29.14	0.30600	349.66	0.795	0.38518	0.464
790308	1900	24.00	13.87	0.17000	332.81	0.757	0.20368	0.245
790224	1300	6.00	55.41	0.56100	332.47	0.756	0.67145	0.809
790406	100	12.00	27.16	0.42400	325.88	0.741	0.49743	0.599
790414	1300	3.00	107.15	1.5430	321.44	0.731	1.7855	2.151
790410	1900	12.00	26.34	0.24600	316.05	0.719	0.27989	0.337
790409	1300	12.00	26.34	0.38400	316.05	0.719	0.43690	0.526
790915	100	24.00	13.13	0.48300	315.12	0.717	0.54794	0.560
790414	1000	3.00	104.79	1.5640	314.37	0.715	1.7700	2.133
790414	1600	3.00	104.27	1.5820	312.82	0.711	1.7816	2.147
790306	100	6.00	51.57	0.27000	309.43	0.704	0.30076	0.362
790305	1300	4.50	68.28	0.34200	307.24	0.699	0.37830	0.456
791209	1900	24.00	12.40	0.32600	297.55	0.677	0.34921	0.421
790224	1900	6.00	47.85	0.51700	287.10	0.653	0.53435	0.644
790622	1300	6.00	47.36	1.3260	284.14	0.646	1.3564	1.634
790622	1900	6.00	46.70	1.1020	280.22	0.637	1.1117	1.339
790309	1900	24.00	11.51	0.16100	276.28	0.628	0.16013	0.193
790223	700	6.00	45.28	0.46000	271.68	0.618	0.44990	0.542
790223	1300	6.00	45.28	0.74400	271.68	0.618	0.72767	0.877
790223	100	6.00	45.28	0.40800	271.68	0.618	0.39904	0.481
790306	700	6.00	43.83	0.24700	262.95	0.598	0.23382	0.282
790621	1900	6.00	43.51	3.4920	261.07	0.594	3.2819	3.954
790409	1900	9.00	28.38	0.32000	255.43	0.581	0.29425	0.355
790623	100	6.00	41.96	0.85600	251.75	0.573	0.77578	0.935
790305	100	3.00	82.36	0.39800	247.08	0.562	0.35401	0.427
790304	2200	3.00	81.29	0.38900	243.88	0.555	0.34152	0.412
790415	400	3.00	81.08	1.5200	243.24	0.553	1.3310	1.604
790305	400	3.00	80.87	0.38000	242.60	0.552	0.33188	0.400
790622	700	6.00	40.43	1.6360	242.59	0.552	1.4288	1.722
790304	1900	3.00	79.76	0.37400	239.29	0.544	0.32218	0.388
790622	100	6.00	39.53	1.8040	237.19	0.539	1.5404	1.850
790304	1600	3.00	77.92	0.37700	233.76	0.532	0.31726	0.382
790305	700	3.00	77.92	0.35700	233.76	0.532	0.30043	0.362
790225	100	6.00	38.94	0.43500	233.63	0.531	0.36586	0.441
790311	1900	21.00	11.08	0.15600	232.76	0.529	0.13072	0.158
790411	700	12.00	12.22	0.18600	230.68	0.525	0.15446	0.186
790415	700	3.00	76.89	1.4240	230.66	0.525	1.1824	1.425
790829	1300	24.00	9.53	0.35100	228.73	0.520	0.28903	0.348
790304	1300	3.00	75.44	0.39000	226.33	0.515	0.31776	0.382
790306	1300	6.00	36.63	0.22800	219.77	0.500	0.18035	0.217
790304	1000	3.00	73.21	0.39700	219.64	0.500	0.31390	0.378
790305	1000	3.00	73.01	0.34400	219.04	0.498	0.27126	0.327
790223	1900	6.00	36.48	0.59000	218.91	0.498	0.46496	0.560

Table 18. Sample printout showing the 50 largest phosphorus fluxes contributing to the phosphorus loading at Melmore during the 1979 water year.

DATE	TIME	MT	FLOW	TP	FLOW VOL	X VOL	FLUX	% FLUX
790621	1900	6.00	43.51	3.49220	261.07	0.594	3.2819	3.954
790414	1900	4.50	97.89	1.49000	440.49	1.002	2.3628	2.847
790414	700	4.50	93.46	1.4660	420.56	0.957	2.2195	2.574
790415	100	4.50	65.60	1.5620	385.22	0.876	2.1662	2.610
790414	100	6.00	68.08	1.3140	408.50	0.929	1.9324	2.328
790414	1300	3.00	107.15	1.5430	321.44	0.731	1.7855	2.151
790414	1600	3.00	104.27	1.5820	312.82	0.711	1.7816	2.147
790414	1000	3.00	104.79	1.5640	314.37	0.715	1.7700	2.133
790622	100	6.00	39.53	1.8040	237.19	0.539	1.5404	1.856
790622	700	6.00	40.43	1.6360	242.59	0.552	1.4288	1.722
790622	1300	6.00	47.36	1.3260	284.14	0.646	1.3564	1.634
790415	400	3.00	81.08	1.5200	243.24	0.553	1.3310	1.604
790415	700	3.00	76.89	1.4240	230.66	0.525	1.1824	1.426
790622	1900	6.00	46.70	1.1020	280.22	0.637	1.1117	1.339
790415	1000	3.00	72.42	1.5840	217.26	0.494	1.0825	1.304
790415	1300	3.00	67.69	1.2480	203.08	0.462	0.91240	1.099
790709	1900	9.00	13.24	1.9580	119.16	0.271	0.83993	1.012
790621	1300	6.00	17.36	2.1440	104.17	0.237	0.80402	0.969
790415	1600	3.00	63.17	1.1480	189.50	0.431	0.78315	0.944
790224	700	6.00	63.90	0.56700	383.41	0.872	0.78261	0.943
790623	100	6.00	41.96	0.85600	251.75	0.573	0.77578	0.935
790224	100	6.00	61.17	0.58600	367.02	0.835	0.77427	0.933
790417	1300	3.00	19.42	3.6020	58.27	0.133	0.75556	0.910
790223	1300	6.00	45.28	0.74400	271.68	0.618	0.72767	0.877
790415	1900	3.00	59.05	1.0760	177.15	0.403	0.68622	0.827
790224	1300	6.00	55.41	0.56100	332.47	0.756	0.67145	0.809
790526	1000	13.50	27.77	0.46300	374.85	0.853	0.62480	0.753
790415	2200	3.00	54.90	1.0100	164.71	0.375	0.59890	0.722
790915	100	24.00	13.13	0.48300	315.12	0.717	0.54794	0.660
790623	700	6.00	36.20	0.70000	217.17	0.494	0.54728	0.659
790416	100	3.00	51.25	0.97600	153.75	0.350	0.54020	0.651
790224	1900	6.00	47.85	0.51700	287.10	0.653	0.53435	0.644
790406	100	12.00	27.16	0.42400	325.88	0.741	0.49743	0.599
790415	400	3.00	47.52	0.91200	142.56	0.324	0.46807	0.564
790223	1900	6.00	36.48	0.59000	218.91	0.498	0.46496	0.560
790405	100	6.00	29.01	0.72500	174.07	0.396	0.45433	0.547
790223	700	6.00	45.28	0.46000	271.68	0.618	0.44993	0.542
790405	1900	21.00	17.84	0.32700	374.72	0.852	0.44112	0.532
790511	100	6.00	14.80	1.3670	88.83	0.202	0.43715	0.527
790409	1300	12.00	26.34	0.38400	316.05	0.719	0.43690	0.526
790416	700	3.00	43.36	0.90400	139.07	0.296	0.42329	0.510
790223	100	6.00	45.28	0.40800	271.68	0.618	0.39904	0.481
790623	1300	6.00	31.18	0.59000	187.09	0.426	0.39737	0.479
790410	700	12.00	29.14	0.33600	349.66	0.795	0.38518	0.464
790305	1900	6.00	59.58	0.29900	357.46	0.813	0.38477	0.464
790305	1300	4.50	68.28	0.34200	307.26	0.599	0.37830	0.456
790225	100	6.00	38.94	0.43500	233.63	0.531	0.36586	0.441
790405	700	6.00	29.14	0.58000	174.83	0.398	0.36504	0.440
790416	1000	3.00	39.68	0.82800	119.05	0.271	0.35485	0.428
790305	100	3.00	82.36	0.39800	247.08	0.562	0.35401	0.427
790306	1900	15.00	30.92	0.21200	463.81	1.055	0.35398	0.427
791209	1900	24.00	12.40	0.32600	297.55	0.677	0.34921	0.421
790606	100	6.00	4.57	3.4760	27.45	0.062	0.34350	0.414
790304	2200	3.00	81.29	0.38900	243.88	0.555	0.34152	0.411
790405	1300	6.00	28.25	0.55600	169.53	0.386	0.33933	0.409

Table 19. Sample printout of a concentration exceedency table for a sample data set from the Melmore station.

DATE TIME	MT	PARAMETER	FLOW	FLUX	SUM OF TIME	PERCENT EXCEED	SUM OF	PERCENT EXCEED
7304130700	12	0.900000E-01	389.67	257622	12.0000	5.096	FLUX	10.123
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	0.287
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	0.527
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	0.847
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	1.174
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	1.740
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	3.221
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	4.929
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	7.734
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	9.045
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	10.680
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	12.289
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	13.527
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	14.898
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	16.329
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	17.823
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	19.379
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	21.005
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	22.694
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	24.441
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	26.259
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	28.141
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	30.089
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	32.105
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	34.189
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	36.341
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	38.561
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	40.851
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	43.211
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	45.641
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	48.141
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	50.711
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	53.351
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	56.051
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	58.811
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	61.631
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	64.511
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	67.451
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	70.451
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	73.511
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	76.631
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	79.811
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	83.051
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	86.351
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	89.711
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	93.131
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	96.611
7304130700	12	0.106000	320.41	352225	24.0000	10.191	FLUX	100.151

same fashion as in the concentration exceedency tables.

For the flux exceedency tables the samples are ranked by instantaneous flux (Table 21). The percent of time fluxes are less than the indicated value are shown in the "Percent Exceedency" column. The relationship between ranked instantaneous fluxes and the total flux or load are shown in the last two columns.

One modification of the flow exceedency output is to substitute a dummy variable equal to one (1) into the concentration column. This converts the sum of the flux into the sum of the flow and the relationship between flow exceedency and total flow can be examined.

Normally the exceedency calculations described above are done on an entire data set. Some potential uses of this type of exceedency data in water quality management are described in subsequent sections of this report.

Flow Duration Table Calculations

The USGS provides daily flow duration tables for its continuous stream gaging stations. Table 22 is an example of such a table for the Fremont stream gaging station. At each station the mean daily flows are divided into 35 classes (0-34). The flow classes represent approximately equal logarithmic increments in flow. The duration tables consist of two parts. In the first part, the number of days in each water year that the mean daily flows fell into each flow class is listed. In the second part, for each flow class there is listed the flow value, the total number of days that the flow was in that class, the accumulated number of days with flows greater than that flow class, and the percent of days with flows greater than that class. Flow duration tables from the USGS are stored in our computer for each station.

One set of programs uses the flow duration tables to calculate mean annual loading. Table 23 is an example of this method as it is applied to the calculation of mean annual loading of total phosphorus at the Fremont Station (Tindall Bridge). The program sorts the entire Fremont total phosphorus data set into the flow intervals between the listed flow class values from the flow duration table. Figure 7 shows alternate flow class values superimposed on a graph showing the relationship of phosphorus concentration to stream flow, expressed on a log scale. The flux weighted mean concentration of total phosphorus for all of the samples with flows in each interval is calculated. The number of samples in that flow interval is listed as N in the table. The concentration for the interval is multiplied by the arithmetic mean flow for the interval. The resulting instantaneous flux is multiplied by the proportion of a year when the flows fall in that flow interval. This is determined by the change in percent flow exceedency between the two flow classes forming the flow interval. This percent of a year is shown as delta percent in the table. Appropriate conversion factors are introduced so that the products are in kg/yr for each flow interval. These are totaled to provide an estimate of the mean annual loading.

One variation of the program results in the calculation of the average concentration rather than the flux weighted mean concentration for each flow interval. In this case, the standard deviation and the standard error of the

Table 22. U. S. Geological Survey Flow Duration Table for the Sandusky River near Fremont.

DISCHARGE IN CUBIC FEET PER SECOND		JURATION TABLE OF DAILY VALUES FOR YEAR ENDING SEPTEMBER 30																																						
MEAN		STATION NUMBER 04140000																																						
SANDUSKY RIVER FREMONT OH																																								
CLASS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34						
YEAR																																								
1924	2	1	5	4	11	20	30	9	9	10	17	18	37	24	16	33	16	18	12	9	12	6	9	6	2															
1925	2	6	11	17	24	40	19	28	52	40	19	3	13	17	9	22	3	5	4	3	3	7	3	1																
1926	1	2	5	5	8	15	9	18	39	17	41	34	22	24	10	37	13	11	5	14	7	7	5	3	2															
1927	1	2	9	9	17	6	11	15	11	39	47	24	24	19	30	17	20	15	15	10	6	9	4	3																
1928	1	14	32	25	23	3	3	7	11	10	37	24	29	15	24	37	13	7	10	5	6	10	7	4	3															
1929	7	12	18	19	14	19	19	46	35	18	8	39	15	9	10	15	9	14	15	8	3	3	1	3	3															
1930	21	35	17	21	13	5	12	13	12	6	26	33	21	13	11	14	15	10	12	9	6	9	7	4	6	2														
1931	5	15	44	3	14	13	27	28	26	30	30	24	16	13	7	6	4	1	5	2	1																			
1932	5	15	16	19	14	21	18	16	15	19	26	23	18	25	11	16	9	8	15	11	11	8	2	1																
1933	4	15	24	23	23	22	14	5	9	14	15	32	19	15	20	18	27	16	6	13	2	6	8	4	2	1														
1934	12	5	27	27	24	53	39	29	12	27	21	10	17	14	14	10	1	9	5	2	2	1																		
1935	16	5	31	17	25	34	30	35	13	26	16	15	19	12	12	15	14	3	3	7	2	1																		
1936	1	11	13	7	5	2	4	5	2	3	1	1	3																											
1939	6	7	14	14	33	20	19	16	34	28	31	20	12	13	13	13	7	12	7	9	8	2	7	5	6	1	4													
1940	1	7	24	18	52	46	17	13	7	15	17	12	18	12	22	12	7	11	8	2	4	3	2	1																
1941	2	4	1	4	7	28	26	31	34	28	26	13	31	35	15	22	15	9	11	8	2	1	2	3																
1942	2	1	1	14	27	34	50	28	29	24	33	18	21	13	15	3	9	6	4	5	3	3	4	6	2	1	2													
1943	2	2	2	15	26	20	10	16	16	18	23	24	25	23	19	24	23	15	8	12	8	2	11	4	3															
1944	5	5	29	17	39	38	57	39	9	10	6	8	13	15	10	11	14	13	5	3	7	6	4	1	1	1														
1945	17	33	36	37	31	29	6	14	8	16	17	10	13	20	13	11	5	5	5	9	9	5	4	1																
1946	2	10	17	4	7	9	15	4	21	58	40	18	18	14	21	19	13	20	9	11	8	8	6	4	1	1	3													
1947	5	12	5	19	8	26	11	36	25	21	19	20	19	14	12	12	14	16	18	14	14	13	3	4	3	2														
1948	4	4	4	16	15	23	26	31	23	26	31	23	22	28	19	10	13	11	9	9	11	7	6	1	1	1														
1949	2	11	23	33	22	11	11	19	14	14	16	26	30	17	29	18	22	16	9	9	5	6	2	2	1															
1950	3	25	43	27	14	7	15	16	13	13	29	16	14	20	23	11	16	11	11	9	12	6	6	2	2	1														
1951	2	4	23	12	19	8	10	6	7	24	14	15	30	24	13	20	19	17	16	10	21	10	15	10	5	9	2	2												
1952	4	5	24	33	14	20	23	17	19	10	17	7	15	15	14	15	10	10	11	15	14	10	6	6	5	6	2													
1953	4	23	13	21	16	20	21	31	21	12	22	9	25	29	19	18	12	8	11	6	5	3	4	2	1	1	1													
1954	6	32	10	35	34	54	22	23	22	11	8	7	8	12	12	8	11	9	12	9	4	5	4	1	1	1	1													
1955	2	16	7	10	17	11	11	29	47	32	35	18	16	9	6	7	10	15	14	9	7	7	5	5	8	1	1													
1956	1	15	6	22	39	32	19	8	22	27	12	14	22	9	18	14	21	7	14	14	7	9	5	3	2	4														
1957	12	9	11	33	25	15	4	12	18	33	25	23	35	39	30	20	24	15	11	12	12	8	8	1	3	2	3													
1958	10	13	6	21	4	19	16	16	25	15	4	15	25	17	14	23	20	10	8	12	6	5	4	1	5	2	4													
1959	8	15	11	12	14	22	14	22	18	17	30	32	34	25	32	17	14	11	13	9	1	9	6	4	6	1														
1960	6	13	11	57	43	42	19	8	9	17	12	15	11	17	18	4	10	6	4	8	9	10	8	4	3	2	1													
1961	29	26	45	22	11	11	18	24	30	24	15	14	12	13	9	16	5	5	7	8	3	4	3	1	1	1														
1962	17	6	12	18	27	21	35	31	32	31	21	16	24	11	9	4	17	4	10	3	4	4	2																	

Table 22 Continued.

STATION NUMBER		DURATION TABLE OF DAILY VALUES FOR YEAR ENDING SEPTEMBER 30																																					
DISCHARGE IN CUBIC FEET PER SECOND																																							
MEAN SANDUSKY RIVER FREQUENT UM																																							
CLASS	YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34			
															NUMBER OF DAYS IN CLASS																								
0	1966								13	19	27	35	40	28	29	20	20	14	15	8	7	6	15	8	7	6	5	5	6	1	4	2	2						
1	1967								44	25	15	8	17	22	14	18	30	25	14	15	17	18	11	14	11	14	11	9	9	7	3	5	1						
2	1968								17	19	17	16	14	33	42	49	34	19	12	9	14	8	13	5	9	4	2	3	2	2									
3	1969								15	21	8	20	6	19	22	34	33	29	24	14	24	17	4	10	5	7	9	4	7	3	2								
4	1970								11	7	10	21	22	20	31	21	14	21	21	23	23	20	19	17	12	8	3	12	7	7	3	2							
5	1971								27	24	22	37	20	21	27	26	22	25	12	17	10	12	10	5	7	9	3	1	2	2	3								
6	1972								3	35	25	13	7	19	37	23	18	30	29	18	12	14	10	10	5	10	7	4	2	1									
7	1973								1	20	11	6	7	5	13	15	24	27	22	25	33	28	23	36	16	20	13	11	7	2									
8	1974								1	3	13	17	24	16	24	20	13	26	33	17	24	17	9	8	13	6	12	5	5	2	4	3							
9	1975								1	2	3	10	21	16	17	11	10	13	19	32	30	25	18	20	16	15	7	7	7	1	3								
10	1976								1	1	14	10	25	42	36	30	31	25	30	32	12	16	7	7	7	6	7	5	4	2	1	1							
11	1977								55	68	42	31	16	16	11	16	9	10	15	8	18	12	7	10	5	7	5	2	1	1									
12	1978								4	14	22	22	20	30	26	27	24	21	21	24	21	20	9	6	5	8	4	5	6	3	5	1	1						
																							</																

VALUE EXCEEDED *P* PERCENT OF TIME

V95 =	26.00
V90 =	36.00
V75 =	66.00
V70 =	86.00
V50 =	230.00
V25 =	740.00
V10 =	2600.00

Table 23. Sample printout of calculation of mean annual loading using flow duration intervals and flux weighted mean concentrations for each interval.

YIELD BY FLOW CLASS		TATION NAME: TINDALL RIVER.R3		PARAMETER:		MEAN CONC		YIELD	
FLOW CLASS	INTERVAL	DELTA	N	MID FLOW	FI	MG/L	MG/L	MG/D	MG/D
34-35	0.0-0.0	0.0	0	29500.00	0.0	0.000000	0.000000	0.000000	0.000000
32-33	0.0-0.0	0.0	0	23000.00	0.0	0.000000	0.000000	0.000000	0.000000
31-32	0.0-0.0	0.0	0	17000.00	0.0	0.000000	0.000000	0.000000	0.000000
30-31	0.0-0.0	0.0	0	12000.00	0.0	0.000000	0.000000	0.000000	0.000000
29-30	0.0-0.0	0.0	0	9000.00	0.0	0.000000	0.000000	0.000000	0.000000
28-29	0.0-0.0	0.0	0	7250.00	0.0	0.000000	0.000000	0.000000	0.000000
27-28	0.0-0.0	0.0	0	5950.00	0.0	0.000000	0.000000	0.000000	0.000000
26-27	0.0-0.0	0.0	0	4550.00	0.0	0.000000	0.000000	0.000000	0.000000
25-26	0.0-0.0	0.0	0	3450.00	0.0	0.000000	0.000000	0.000000	0.000000
24-25	0.0-0.0	0.0	0	2050.00	0.0	0.000000	0.000000	0.000000	0.000000
23-24	0.0-0.0	0.0	0	1600.00	0.0	0.000000	0.000000	0.000000	0.000000
22-23	0.0-0.0	0.0	0	1200.00	0.0	0.000000	0.000000	0.000000	0.000000
21-22	0.0-0.0	0.0	0	900.00	0.0	0.000000	0.000000	0.000000	0.000000
20-21	0.0-0.0	0.0	0	700.00	0.0	0.000000	0.000000	0.000000	0.000000
19-20	0.0-0.0	0.0	0	540.00	0.0	0.000000	0.000000	0.000000	0.000000
18-19	0.0-0.0	0.0	0	410.00	0.0	0.000000	0.000000	0.000000	0.000000
17-18	0.0-0.0	0.0	0	310.00	0.0	0.000000	0.000000	0.000000	0.000000
16-17	0.0-0.0	0.0	0	240.00	0.0	0.000000	0.000000	0.000000	0.000000
15-16	0.0-0.0	0.0	0	180.00	0.0	0.000000	0.000000	0.000000	0.000000
14-15	0.0-0.0	0.0	0	140.00	0.0	0.000000	0.000000	0.000000	0.000000
13-14	0.0-0.0	0.0	0	100.00	0.0	0.000000	0.000000	0.000000	0.000000
12-13	0.0-0.0	0.0	0	80.00	0.0	0.000000	0.000000	0.000000	0.000000
11-12	0.0-0.0	0.0	0	60.00	0.0	0.000000	0.000000	0.000000	0.000000
10-11	0.0-0.0	0.0	0	40.00	0.0	0.000000	0.000000	0.000000	0.000000
9-10	0.0-0.0	0.0	0	30.00	0.0	0.000000	0.000000	0.000000	0.000000
8-9	0.0-0.0	0.0	0	20.00	0.0	0.000000	0.000000	0.000000	0.000000
7-8	0.0-0.0	0.0	0	15.00	0.0	0.000000	0.000000	0.000000	0.000000
6-7	0.0-0.0	0.0	0	10.00	0.0	0.000000	0.000000	0.000000	0.000000
5-6	0.0-0.0	0.0	0	7.50	0.0	0.000000	0.000000	0.000000	0.000000
4-5	0.0-0.0	0.0	0	5.75	0.0	0.000000	0.000000	0.000000	0.000000
3-4	0.0-0.0	0.0	0	4.00	0.0	0.000000	0.000000	0.000000	0.000000
2-3	0.0-0.0	0.0	0	3.00	0.0	0.000000	0.000000	0.000000	0.000000
1-2	0.0-0.0	0.0	0	2.00	0.0	0.000000	0.000000	0.000000	0.000000
0-1	0.0-0.0	0.0	0	1.00	0.0	0.000000	0.000000	0.000000	0.000000
					2244.				

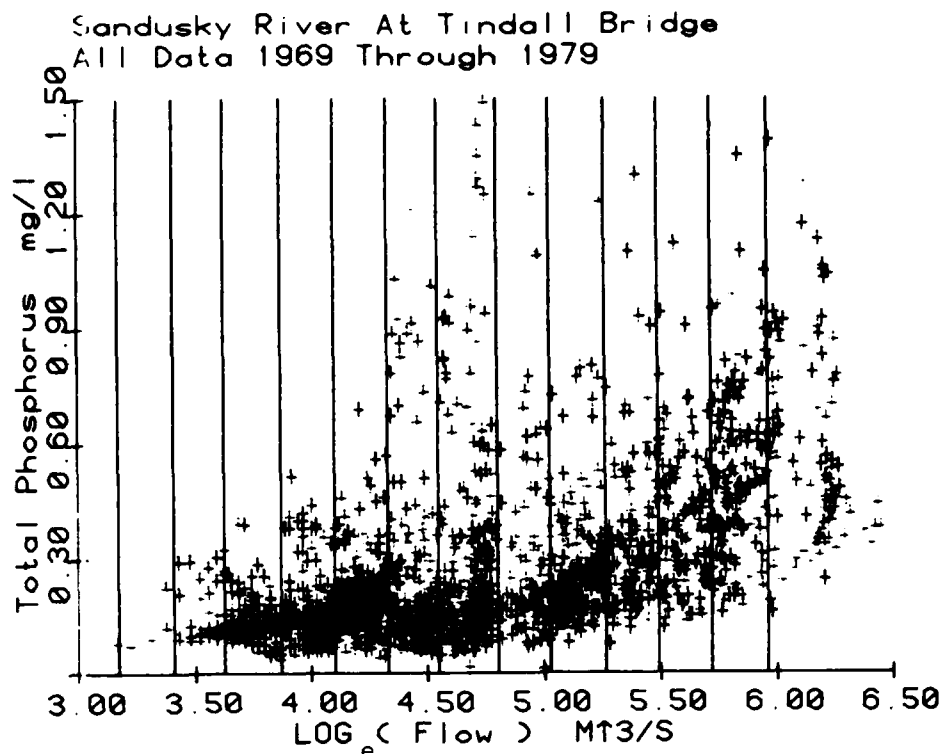


Figure 7. Flow duration flow class intervals for the Fremont gaging station superimposed on a graph of total phosphorus concentration versus log of stream flow.

mean are also calculated for each interval. The standard error of the mean concentration for each flow interval is also multiplied by the mean flow and percent of the year to obtain an error estimate for each interval. These error estimates are totaled for all of the flow intervals to obtain an error estimate for the mean annual load as shown in Table 24.

A second variation sorts the data into summer and winter months. The average concentrations and standard errors are calculated for each flow interval. These seasonal concentration data are used to compare winter and summer concentrations and to calculate fluxes in cases where chemical data are missing. Summer and winter concentration data are stored for each parameter for each flow interval for each station. After entering the station, month and mean daily flow, the program generates an estimated daily flux for each parameter. The program totals the fluxes for each parameter for each mean daily flow entered in a given month. Fluxes for missing sample days are then added to measured fluxes for each month in order to estimate total monthly and annual loads.

Table 24. Sample printout of calculation of mean annual loading of total phosphorus using flow duration tables and average concentrations, standard deviations and standard errors for each interval.

YIELD BY FLOW CLASS										
STATION NAME: TINCALL.RIVER.R3										
PARAMETER: TP										
FLOW CLASS	INTERVAL	DELTA	N	MID FLOW PI*5/SEC	TOTAL FLOW	MEAN CONC MG/L	YIELD MG/YR	SDX MEAN	SFEAR MEAN	SFEAR YIELD
1	0-10	0.0	0	29500.00	0.00	0.000	0.000	0.000	0.000	0.000
2	10-20	0.0	0	23000.00	0.00	0.000	0.000	0.000	0.000	0.000
3	20-30	0.0	0	17500.00	0.00	0.000	0.000	0.000	0.000	0.000
4	30-40	0.0	0	13000.00	0.00	0.000	0.000	0.000	0.000	0.000
5	40-50	0.0	0	9900.00	0.00	0.000	0.000	0.000	0.000	0.000
6	50-60	0.0	0	7750.00	0.00	0.000	0.000	0.000	0.000	0.000
7	60-70	0.0	0	5950.00	0.00	0.000	0.000	0.000	0.000	0.000
8	70-80	0.0	0	4550.00	0.00	0.000	0.000	0.000	0.000	0.000
9	80-90	0.0	0	3650.00	0.00	0.000	0.000	0.000	0.000	0.000
10	90-100	0.0	0	2650.00	0.00	0.000	0.000	0.000	0.000	0.000
11	100-110	0.0	0	1600.00	0.00	0.000	0.000	0.000	0.000	0.000
12	110-120	0.0	0	1200.00	0.00	0.000	0.000	0.000	0.000	0.000
13	120-130	0.0	0	700.00	0.00	0.000	0.000	0.000	0.000	0.000
14	130-140	0.0	0	540.00	0.00	0.000	0.000	0.000	0.000	0.000
15	140-150	0.0	0	315.00	0.00	0.000	0.000	0.000	0.000	0.000
16	150-160	0.0	0	240.00	0.00	0.000	0.000	0.000	0.000	0.000
17	160-170	0.0	0	185.00	0.00	0.000	0.000	0.000	0.000	0.000
18	170-180	0.0	0	107.00	0.00	0.000	0.000	0.000	0.000	0.000
19	180-190	0.0	0	63.00	0.00	0.000	0.000	0.000	0.000	0.000
20	190-200	0.0	0	37.00	0.00	0.000	0.000	0.000	0.000	0.000
21	200-210	0.0	0	22.00	0.00	0.000	0.000	0.000	0.000	0.000
22	210-220	0.0	0	17.00	0.00	0.000	0.000	0.000	0.000	0.000
23	220-230	0.0	0	11.00	0.00	0.000	0.000	0.000	0.000	0.000
24	230-240	0.0	0	6.00	0.00	0.000	0.000	0.000	0.000	0.000
25	240-250	0.0	0	3.00	0.00	0.000	0.000	0.000	0.000	0.000
26	250-260	0.0	0	1.00	0.00	0.000	0.000	0.000	0.000	0.000
27	260-270	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
28	270-280	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
29	280-290	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
30	290-300	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
31	300-310	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
32	310-320	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
33	320-330	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
34	330-340	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
35	340-350	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
36	350-360	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
37	360-370	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
38	370-380	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
39	380-390	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
40	390-400	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
41	400-410	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
42	410-420	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
43	420-430	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
44	430-440	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
45	440-450	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
46	450-460	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
47	460-470	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
48	470-480	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
49	480-490	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
50	490-500	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
51	500-510	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
52	510-520	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
53	520-530	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
54	530-540	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
55	540-550	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
56	550-560	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
57	560-570	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
58	570-580	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
59	580-590	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
60	590-600	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
61	600-610	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
62	610-620	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
63	620-630	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
64	630-640	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
65	640-650	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
66	650-660	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
67	660-670	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
68	670-680	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
69	680-690	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
70	690-700	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
71	700-710	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
72	710-720	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
73	720-730	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
74	730-740	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
75	740-750	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
76	750-760	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
77	760-770	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
78	770-780	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
79	780-790	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
80	790-800	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
81	800-810	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
82	810-820	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
83	820-830	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
84	830-840	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
85	840-850	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
86	850-860	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
87	860-870	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
88	870-880	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
89	880-890	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
90	890-900	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
91	900-910	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
92	910-920	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
93	920-930	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
94	930-940	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
95	940-950	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
96	950-960	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
97	960-970	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
98	970-980	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
99	980-990	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
100	990-1000	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
101	1000-1010	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
102	1010-1020	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
103	1020-1030	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
104	1030-1040	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
105	1040-1050	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
106	1050-1060	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
107	1060-1070	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
108	1070-1080	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
109	1080-1090	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
110	1090-1100	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
111	1100-1110	0.0	0	0.00	0.00	0.000	0.000	0.000	0.000	0.000
112	1110-1120	0.0	0							

SECTION 6

CONCENTRATIONS OF NUTRIENTS AND SEDIMENTS AT THE TRANSPORT STATIONS

Studies of both ambient water quality and material transport in streams require measurements of the concentrations of various substances. For nutrients and sediments in the streams of northwestern Ohio, a major feature of the concentration data is the large amount of variability present at a given station. This variability is reflected in the graphs showing the relationship between concentrations of various materials and stream flow (Figure 8). Examination of the concentration data reveals that, within this variability, there exist several patterns of concentration in relation to flow, location and time. In this section of the report these patterns of concentration are presented along with a discussion of some of the factors which contribute to the variability.

DESCRIPTION OF DATA SETS

The extent of the data available at each of the transport stations is summarized in Table 25. The summary includes the number of nutrient and sediment samples analyzed during each water year for which automatic samplers were in place at the sampling stations. The total discharge for each water year as monitored by the USGS is listed. The percent of the total discharge and time monitored at each station for each water year was calculated from the total flow and total time data listed in the flux summaries for suspended solids. Only data collected through the 1979 water year have been included in the data analyses presented in this report. The sampling and analyses program did continue at eight of the stations during the 1980 and 1981 water years. In addition to the parameters listed in Table 25, conductivity, pH and ammonia data are also available for approximately the same numbers of samples. Chloride, sulfate and total Kjeldahl nitrogen data are available for approximately 25% of the samples.

TYPES OF WEIGHTED AVERAGE SEDIMENT AND NUTRIENT CONCENTRATIONS

As noted in the description of the flux summary programs, four types of average concentrations are calculated for each data set. The equations for calculating these average concentrations are repeated below.

1. Average Concentration (unweighted)

$$\bar{C} = \frac{\sum c_i}{n}$$

2. Time Weighted Average Concentration

$$\bar{C} = \frac{\sum c_i t_i}{\sum t_i}$$

Table 25. Numbers of Samples Analyzed and Percent of Flow and Time Monitored by Water Year for Northwestern Ohio Sampling Stations.

	Water Year	Discharge 10 ³ m ³	Percent Monitored		Suspended Solids	Numbers of Samples Analyzed			
			% Flow	% Time		Total Phosphorus	Soluble Reactive Phosphorus	Nitrate Nitrogen	Conductivity
Maumee	1975	476.3	73 _a	59 _a	386	396	413	397	368
	1976	503.5	86	90	601	615	585	604	617
	1977	305.3	70	69	406	407	395	382	398
	1978	616.6	96	78	418	418	405	414	418
Portage	1975	28.99	69	57	465	427	487	502	488
	1976	32.62	81	82	565	565	566	563	575
	1977	24.13	78	71	381	380	361	360	370
	1978	44.38	98	82	445	444	436	445	445
Bucyrus	1975	10.27	35	31	119	118	121	122	118
	1976	8.21	78	66	529	519	537	524	516
	1977	5.4	97	84	575	575	513	560	578
	1978	9.55	99	89	500	501	455	478	503
	1979	12.03	58	54	336	330	330	336	335
Nevada	1976	4.83	86	60	458	464	440	473	490
	1977	5.21	79	75	512	513	479	487	517
	1978	12.25	65	73	429	430	423	431	431
	1979	9.91	90	64	456	455	455	454	456
Upper Sandusky	1975	27.53	92 _a	72 _a	621	572	631	631	621
	1976	22.05	91	79	647	635	622	630	640
	1977	14.11	113	88	558	535	552	550	559
	1978	30.68	72	69	384	385	380	386	378
	1979	27.57	81	76	486	488	488	483	488
Tymochtee	1975	17.71	89	58	555	535	576	580	567
	1976	7.64	67	64	428	454	412	433	457
	1977	6.60	99	82	484	482	466	486	491
	1978	20.73	73	80	408	413	390	419	420
	1979	14.42	76	61	323	323	323	324	323
Mexico	1975	56.66		8	105	132	129	132	128
	1976	47.83			413	412	384		
	1977	36.07		50	315	332	315	332	331
	1978	75.13							
	1979	63.75	6	76	436	437	436	436	437
Melmore	1976	6.91	121	63	477	477	470	477	483
	1977	7.29	112	89	656	668	658	667	660
	1978	14.78	109	96	554	555	539	555	555
	1979	15.02	105	80	569	570	570	569	570

Table 25 continued

	Water Year	Discharge 10^7 m^3	Percent Monitored		Suspended Solids	Numbers of Samples Analyzed			
			% Flow	% Time		Total Phosphorus	Soluble Reactive Phosphorus	Nitrate Nitrogen	Conductivity
Wolf West	1976	3.01	80%	55%	382	388	378	366	388
	1977	2.85	86	80	467	446	462	466	468
	1978	6.74	91	72	437	435	428	438	436
	1979	4.59	105	64	413	415	411	414	415
Wolf East	1976	4.40	99	57	372	358	345	371	363
	1977	11.50	99	74	486	487	481	466	489
	1978	11.21	46	73	411	412	404	407	412
	1979	6.27	67	68	385	388	388	388	389
Fremont	1975	103.0	67	51	421	397	426	403	406
	1976	77.16	54	68	433	426	416	429	423
	1977	62.90	93	84	452	450	444	455	456
	1978	139.1	83	83	456	455	446	454	456
	1979	108.8	83	62	420	424	422	423	423
Huron	1975	30.58	80	60	568	552	586	546	546
	1976	26.71	83	84	560	518	521	538	560
	1977	25.35	86	62	346	339	317	328	345
	1978	40.48	87	75	377	379	374	379	377
	1979	29.55	27	31	176	175	171	176	168

3. Flow Weighted Average Concentration

$$\bar{C} = \frac{\sum C_i q_i}{\sum q_i}$$

4. Flux Weighted Average Concentration

$$\bar{C} = \frac{\sum C_i q_i t_i}{\sum q_i t_i}$$

where C_i = concentration of i th sample; q_i = instantaneous flow for i th sample; and t_i = time multiplier for i th sample; and n = number of samples.

The necessity of distinguishing among four different methods of calculating average concentrations is a consequence of the nature of the sampling program used in this study. In order to accurately measure stream transport, the frequency of collections during high stream flows was greater than the frequency during low flows. Consequently, the individual samples have varying time durations associated with them. If the samples had been collected on a uniform time schedule (as for example daily or weekly) then equations 1 and 2 would have been identical as would equations 3 and 4.

In Table 26 the four methods are illustrated using the data from the Melmore gaging station. The average and time weighted average concentrations provide information of relevance for ambient water quality. If, for example, water were to be withdrawn at a constant rate from the river, the time weighted average concentrations in the stream would reflect the average concentrations of the pumped water. In contrast, the flow weighted and flux weighted average concentrations provide information of relevance to stream transport. If all of the water discharged by the stream were collected for a long period of time, the flux weighted concentration in the stream would be the average concentration of the collected water.

Comparison of the flux weighted and time weighted average concentrations also indicates whether the concentrations of a given parameter tend to increase or decrease with increasing stream flows. Where the flux weighted average concentration exceeds the time weighted concentration, as for suspended solids, total phosphorus and nitrates, the concentration of the parameter tends to increase with increasing stream flow. Conductivity and chlorides (not shown) tend to decrease in concentration as stream flow increases. For these the flux weighted concentration is less than the time weighted concentration. The time and flux weighted concentrations of soluble reactive phosphorus are almost equal, indicating that at the Melmore gaging station the soluble reactive phosphorus is, on the average, independent of stream flow.

In Table 27 the time and flux weighted average concentration of sediments and nutrients are listed for each of the twelve sampling stations. In each case the concentration is calculated from the entire data set available for the station through the 1979 water year. This includes both the full year records described in Table 25 and partial year records from earlier water

Table 26. Comparison of time weighted average, flow weighted average and flux weighted average concentrations of sediment and nutrients at the Honey Creek, Melmore sampling station for the period between 76-01-28 and 79-09-30.*

Parameter	N	Average mg/l	Time Wt. Average mg/l	Flow Wt. Average mg/l	Flux Wt. Average mg/l
Suspended Solids	2256	99.6	56.3	203.7	164.17
Total Phosphorus	2270	.271	.193	.466	.386
Souble Reactive P.	2237	.0861	.0781	.0851	.0789
Nitrate/Nitrite N	2268	4.30	3.68	4.56	4.57
Conductivity (umhos)	2268	518	585	320	379
Ammonia-N	2216	.208	.187	.293	.241

*The average concentrations reported in this table were calculated after the addition of missing flow data based on U. S. Geological Survey estimates of mean daily flows. Consequently, these average values are slightly different than those presented in other tables. See section 7 for further description of corrections for missing data.

years. The number of samples included in the calculations for suspended solids is listed for each station. Similar numbers of samples were used for the nutrient calculations. Those stations located downstream from significant municipal sewage outfalls are evident as locations where the time weighted mean concentrations of soluble reactive phosphorus are larger than the flux weighted mean concentrations. This occurs at the Portage, Bucyrus, Upper Sandusky and Huron stations.

PATTERNS OF SEDIMENT AND NUTRIENT CONCENTRATIONS IN RELATION TO STREAM FLOW

Typical relationships between sediment and nutrient concentrations and stream flow for northwestern Ohio rivers are shown in the scattergrams of Figure 8. The patterns for strictly agricultural watersheds are illustrated by the East Branch of Wolf Creek (upper graphs) while the patterns for agricultural watersheds containing significant point sources immediately upstream from the sampling station are illustrated by the West Branch of Wolf Creek (lower graphs). The Wolf-West sampling station is immediately downstream from the town of Bettsville. In this figure a log (base 10) scale is used for stream flow so that the points will be spread out across the graphs rather than concentrated on the left (low flow) portion of the graph. Because of the log scale for flow, care must be exercised in judging the presence or absence of trends in the data. The graphs include all of the data for the Wolf-East and West stations summarized in Table 25. Note that in

Table 27. Comparison of Flux Weighted and Time Weighted Mean Concentrations of Suspended Solids and Nutrients in Northwestern Ohio River Basins.

Gaging Station		N	Suspended Sediment mg/l	Total Phosphorus mg/l	Soluble Reactive P. mg/l	NO ₃ -NO ₂ Nitrogen mg/l	Conduc- tivity umhos
Maumee, Waterville	Flux Wt. Mean	1769	242	.516	.116	4.92	517
	Time Wt. Mean		106	.340	.116	3.91	652
Portage, Woodville	Flux Wt. Mean	1842	164	.402	.119	5.89	554
	Time Wt. Mean		62	.360	.191	3.80	854
Huron, Milan	Flux Wt. Mean	2027	220	.362	.104	3.61	540
	Time Wt. Mean		69.6	.343	.201	2.50	685
Sandusky, Fremont	Flux Wt. Mean	2237	217	.453	.093	4.61	487
	Time Wt. Mean		83.1	.244	.073	3.09	716
Sandusky, Mexico	Flux Wt. Mean	1578	239	.428	.070	3.50	624
	Time Wt. Mean		85.8	.250	.069	3.49	750
Sandusky, Upper S.	Flux Wt. Mean	2729	235	.518	.134	3.90	478
	Time Wt. Mean		105	.482	.234	2.60	709
Sandusky, Bucyrus	Flux Wt. Mean	2299	173	.573	.219	3.42	460
	Time Wt. Mean		49.6	1.13	.837	3.11	702
Tymochtee, Crawford	Flux Wt. Mean	2631	205	.419	.069	5.12	397
	Time Wt. Mean		68.7	.181	.040	7.48	751
Honey Cr., Melmore	Flux Wt. Mean	2115	180	.403	.101	4.85	397
	Time Wt. Mean		57.8	.195	.102	3.74	587
Broken Sword, Nevada	Flux Wt. Mean	1766	244	.401	.061	4.87	428
	Time Wt. Mean		78.3	.157	.042	3.11	627
Wolf Cr., East Br.	Flux Wt. Mean	1654	181	.416	.118	4.71	578
	Time Wt. Mean		42.4	.161	.063	2.92	764
Wolf Cr., West Br.	Flux Wt. Mean	1699	183	.394	.100	6.14	464
	Time Wt. Mean		40.8	.232	.133	3.45	747

several instances the scaling factors (Scientific notation with E format) vary for both concentrations and flows.

The pattern for suspended solids (Figure 8) is similar for both streams. The suspended solid concentrations are low at low flows and increase as the flows increase. The concentrations are very variable at a given flow, particularly at the higher flow values. This pattern reflects the relationship between rainfall induced erosion on the landscape and sediment transport by the storm runoff water in the streams. The effects of resuspension sediment as stream flows increase and of stream bank erosion may also contribute to the observed pattern.

For the East Branch of Wolf Creek the pattern of total phosphorus concentrations (Figure 8b) in relation to stream flow is very similar to the sediment pattern. Much of the total phosphorus is particulate phosphorus that is adsorbed onto sediment particles. For the West Branch, the total phosphorus concentration is lowest in the midrange of flows and increases as the flows both increase and decrease. The high total phosphorus concentrations at low flows are due to point source inputs of phosphorus. As the stream flows decrease, there is less stream water present to dilute the incoming point sources. The high concentrations of total phosphorus at high flows are related to the high sediment concentrations and are similar to those found in the East Branch.

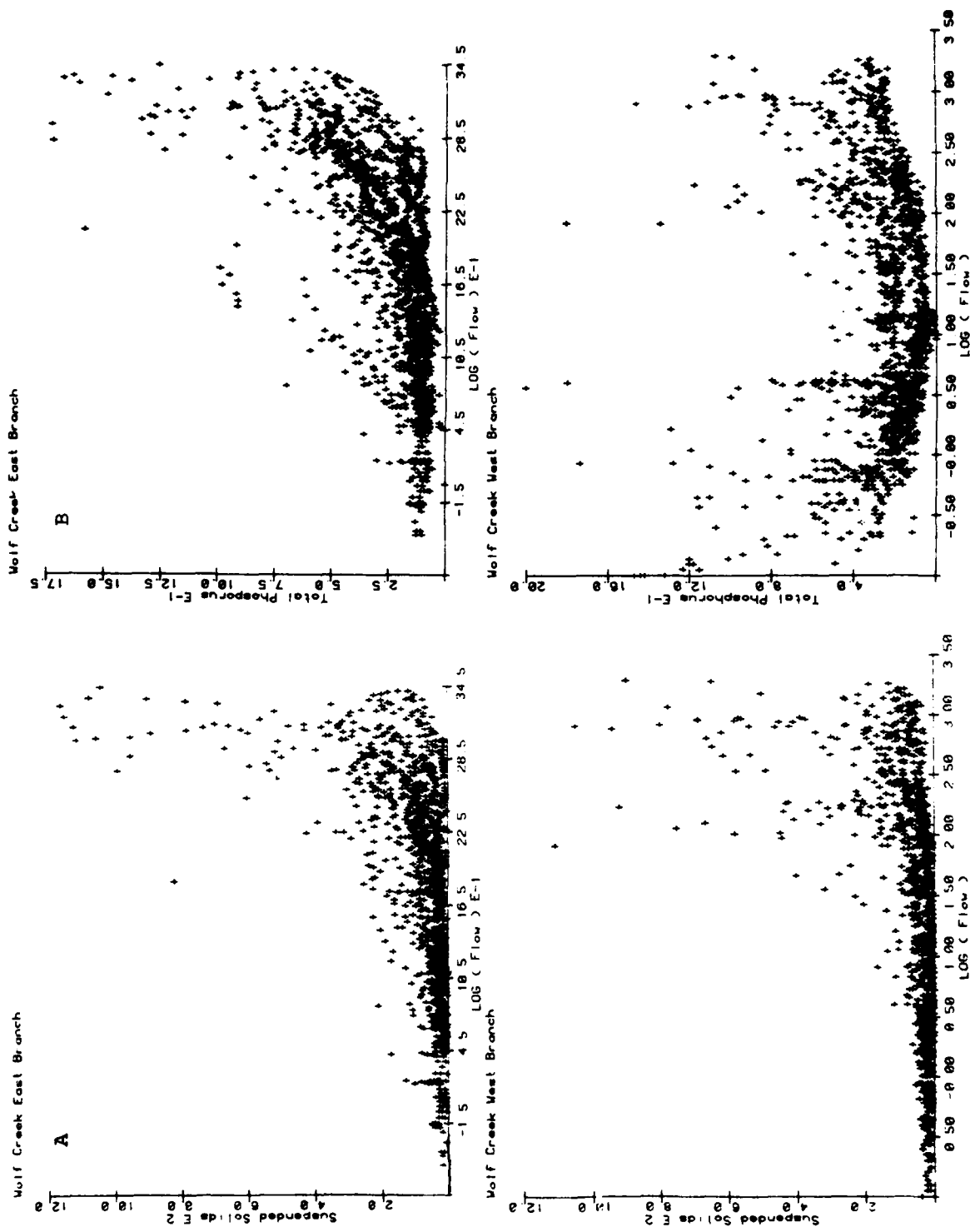


Figure 8. Relationship of concentrations (mg/l) and log flow in CFS at the Wolf, East and West Stations.

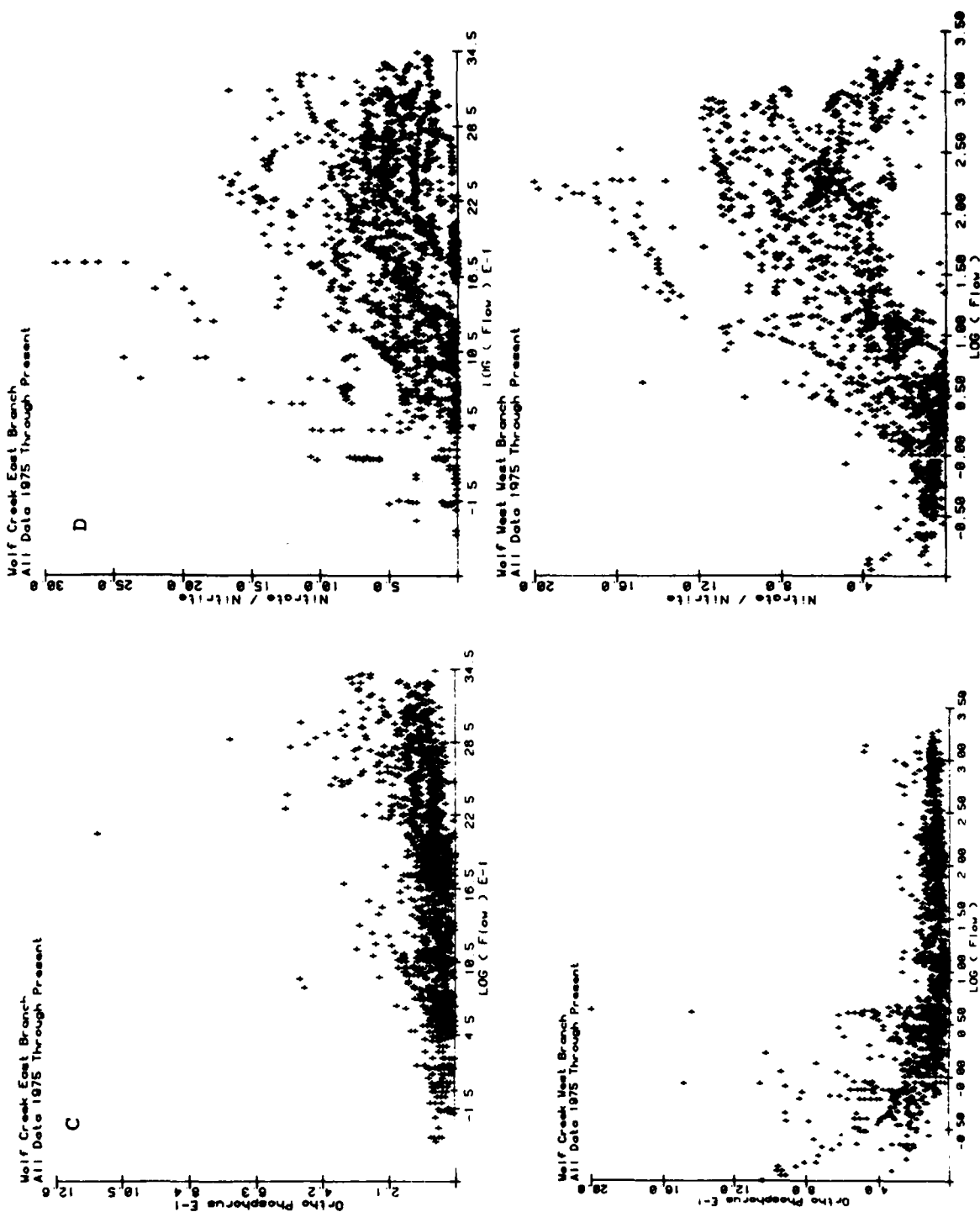


Figure 8 continued.

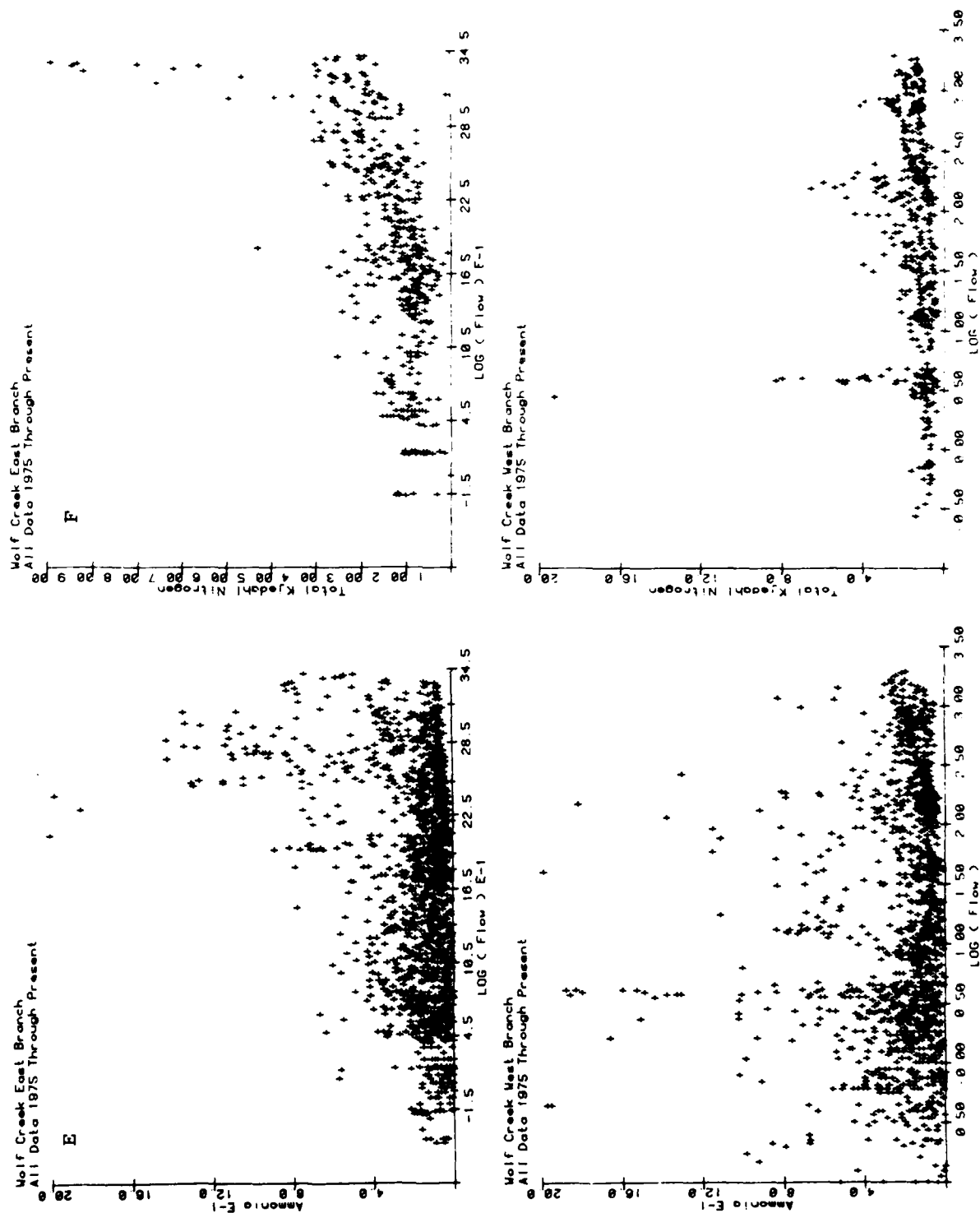


Figure 8 continued.

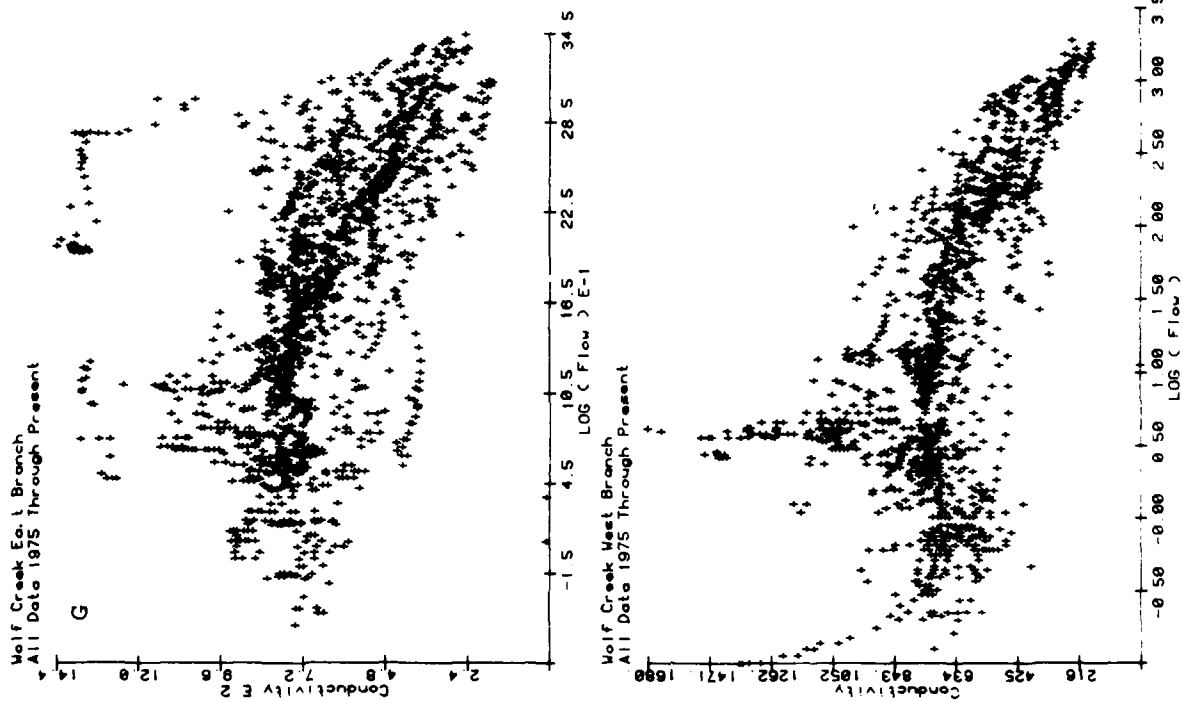


Figure 8 continued.

The concentrations of soluble reactive phosphorus in the East Branch do increase slightly as stream flows increase (Figure 8c). This increase is not nearly as large as the increase in total phosphorus concentrations with increasing stream flow. Not all of the agricultural watersheds show increasing soluble reactive phosphorus concentrations with increasing stream flow, but in all of them the soluble reactive phosphorus concentrations are significant during periods of high stream flow. For the West Branch of Wolf Creek the dominant feature of the soluble reactive phosphorus concentration versus flow graph is the large increase at low stream flows. During the low flows below point source inputs a large proportion of the total phosphorus is in the form of soluble reactive phosphorus. Point source sewage effluents are characterized by a high proportion of soluble reactive phosphorus present within the total phosphorus.

The patterns of nitrate + nitrite nitrogen concentrations are similar for the two streams (Figure 8d). In both cases the nitrates tend to increase as stream flows increase but the concentrations are extremely variable at all flows. The point source inputs at Bettsville do not cause increases in nitrate concentrations under low flow conditions on the West Branch of Wolf Creek.

The patterns for ammonia nitrogen (Figure 8e) are similar to those for total phosphorus except that they are less pronounced. For the East Branch the highest ammonia concentrations did occur under conditions of high flow. These would reflect occasional high ammonia concentrations in runoff water from agricultural lands. However, many low values for ammonia were also observed at high flows. High ammonia concentrations are also characteristic of sewage effluent and consequently in the West Branch of Wolf Creek, high ammonia concentrations were present at both high and low flows.

The concentration-flow pattern for Total Kjeldahl Nitrogen (TKN) paralleled the sediment patterns in the East Branch (Figure 8f). For the West Branch, some high TKN values were also observed under low flows. (Note that different TKN concentration scales were used for the two stations). Significant nitrogen export does occur in the TKN fraction associated with suspended solids.

For both of the stations conductivity decreased as stream flows increased (Figure 8g). Again considerable variability was present in the conductivity at a given flow. A number of factors probably account for the conductivity patterns. The conductivities of surface runoff water would be less than tile effluent which, in turn, would be less than ground water. Various mixtures of water from the above three sources would produce varying conductivities. Under low flow conditions evaporation in the summer and ice formation in the winter can increase the conductivity of the stream water.

The patterns of concentration versus flow illustrated for the two branches of Wolf Creek are typical of the patterns observed at the other transport stations in northwestern Ohio. The major variations in the patterns are associated with the extent of point source impact under low flow conditions. As the volume of the point source discharge increases in relation to stream flow and as the concentrations of the point source effluent increase in relationship to background stream concentrations, the effects of the point source effluents on the concentration versus flow patterns become larger.

However, the further downstream the sampling station is located relative to the point source outfall, the less will be the impact on the low flow stream concentrations. This is especially so for nonconservative parameters, such as phosphorus and nitrogen, which are processed in various ways by the stream system.

Although various types of concentration-flow patterns are evident in the scattergrams described above, the large amounts of variability in sediment and nutrient concentrations at a given station and flow rate stand out as important features of the data sets. It is evident that basing conclusions concerning stream chemistry on the results of sampling programs involving small numbers of samples could give misleading results. In the following sections, sources of this variability in concentration-flow relationships will be discussed.

HYDROGRAPHS, SEDIMENTGRAPHS AND CHEMOGRAPHS

Part of the variability in chemical concentrations at a given station and flow is due to the nature of the runoff events which move through stream systems. As a storm event moves past a given sampling station, the stream flow and concentrations of sediment and various chemicals change in characteristic ways. A given flow less than the peak flow will occur twice, once during rising flows and once during falling flows. The chemical concentrations during these two periods are often quite different. Plots illustrating the changes in stream flow, sediment concentration and concentrations of chemicals as a function of time are referred to as hydrographs, sedimentgraphs and chemographs. Where the chemicals are considered pollutants the term "pollutograph" is also used. Analysis of these graphs can often yield information concerning the source and transport of materials.

Figure 9 shows a typical runoff event which occurred between May 2 and May 11, 1977 on the East Branch of Wolf Creek. In these figures, the sediment graphs and various chemographs are shown in relationship to the hydrographs. The hydrograph can be divided into the ascending limb, the peak discharge and the descending limb. In a runoff from a single rainstorm the rise in flow on the ascending limb is usually steeper than the decrease in flow on the descending limb and consequently the ascending limb transports less total volume of water and lasts a shorter time than the descending limb. Accordingly, the midpoint in the mass of water moving past a sampling station during a storm event occurs after the peak discharge has passed.

The concentration of suspended sediment increases very rapidly during the ascending limb of the hydrograph (Figure 9a). The peak sediment concentration occurs prior to the peak discharge and the sediment is said to have an "advanced" peak. After the peak sediment concentration is reached the sediment concentration decreases more slowly. The chemographs for total phosphorus (Figure 9b) and Total Kjeldahl Nitrogen (Figure 9c) closely parallel the sediment graph. Much of the total phosphorus is associated with the transport of particulates.

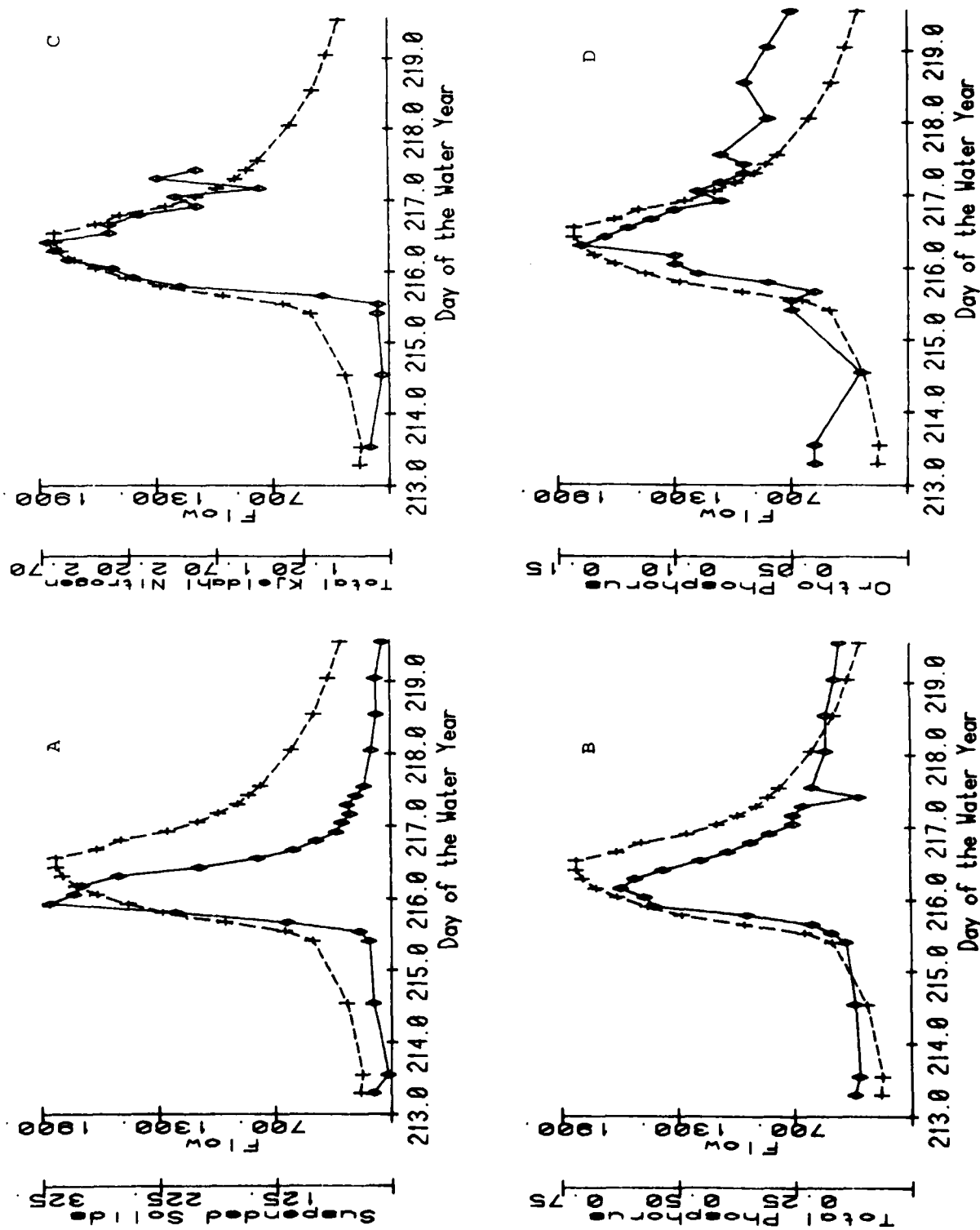


Figure 9. Hydrographs (+), sediment graphs (◊), and chemographs (○) for a runoff event at the Wolf East Station between May 2 and May 11, 1977. Concentrations in mg/l or umhos and flow in CFS.

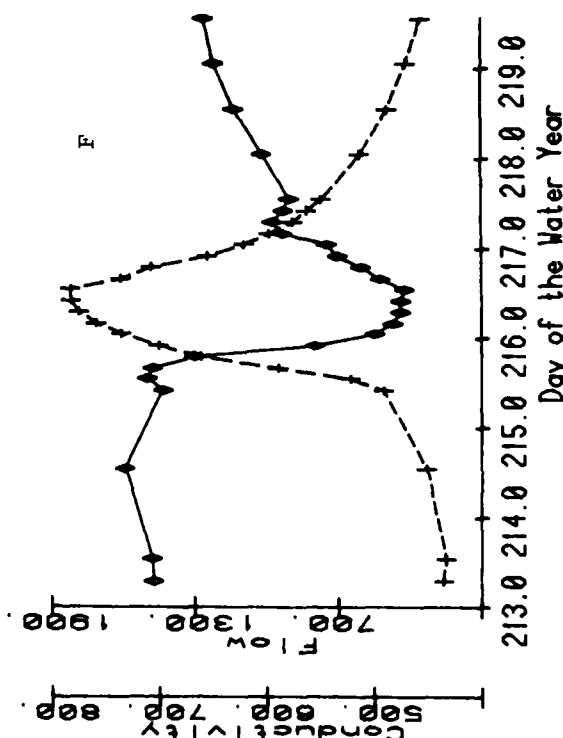
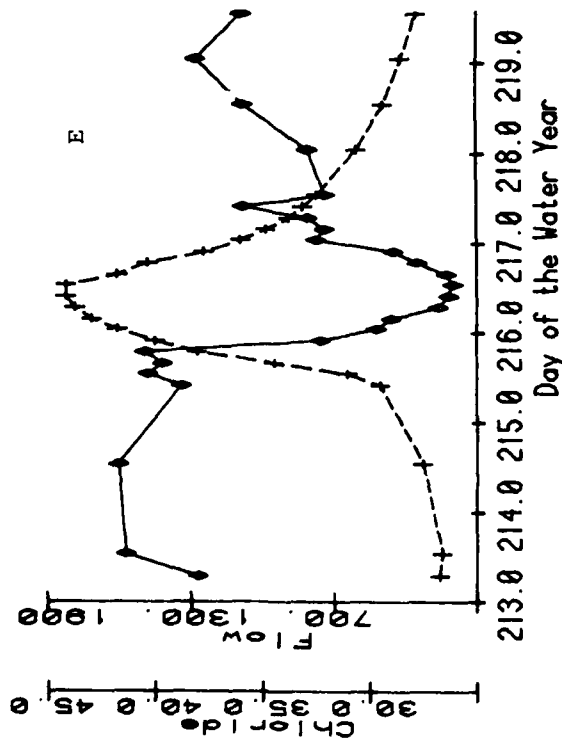
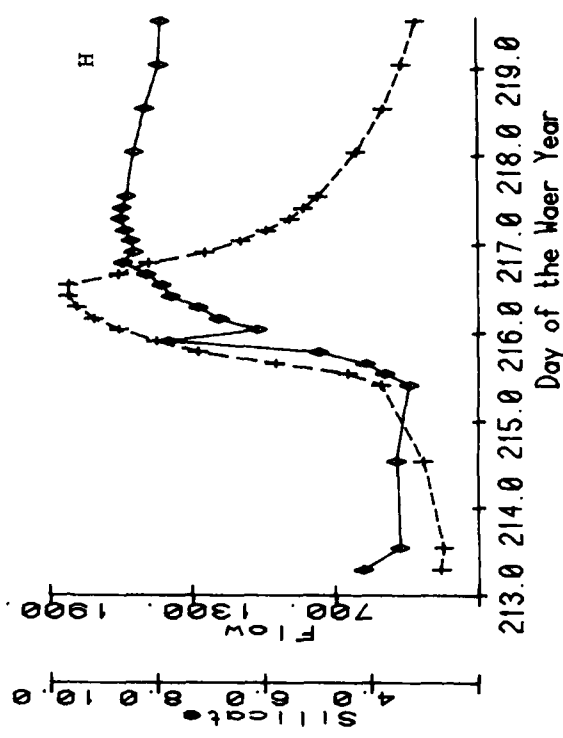
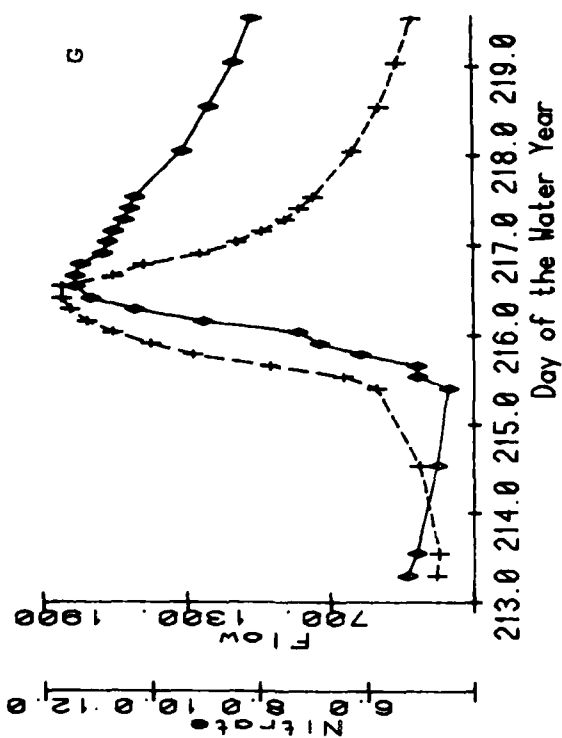


Figure 9 continued.

In contrast to total phosphorus, the chemographs for chloride (Figure 9e) and for conductivity (Figure 9f) show decreasing concentrations as the flow increases. Often the shape of these chemographs is the inverse of the hydrographs. The chemograph for nitrate plus nitrite nitrogen (Figure 9g) shows an increase in concentration in association with the hydrograph. The peak nitrate concentration trails the peak sediment and total phosphorus concentrations and occurs during the descending limb of the hydrograph.

Soluble reactive phosphorus (Figure 9d) also increases in concentration as the flow increases. It should be noted that the actual concentrations of soluble reactive phosphorus are much lower than the total phosphorus concentrations. After its peak, the concentration of the soluble reactive phosphorus decreases more rapidly than the nitrate concentration. The timing of the elevated soluble reactive phosphorus concentrations is more like the timing of the elevated concentrations of suspended sediments and total phosphorus than like nitrate concentrations.

The changes in concentrations which occurred during the runoff event illustrated in Figure 9 represents the net effect of several different processes. Prior to the rainstorm the stream channel upstream from the sampling station contained water with the chemical composition characteristic of low or base flow for the watershed. This water is characterized by high concentrations of chloride, high conductivity and low suspended sediment and nutrient concentrations. During the runoff event, this base flow water in the stream channel would have been pushed ahead by the storm runoff water. The flow of this water would actually have increased during the initial portion of the hydrograph, and subsequently decreased below the pre-storm discharge during the midportion of the storm event.

As the rainfall input to the watershed exceeds the infiltration capacity of the soils, water accumulating on the surface begins to drain into the stream network. This surface runoff water contains high concentrations of sediment and sediment-bound chemicals such as phosphorus. Since this water has limited internal contact with the soil prior to reaching the drainage network it does not contain high concentrations of dissolved substances. The decreasing chloride and conductivity at the sampling station reflects the effects of this surface runoff water, as well as rainwater falling directly on the surface waters. Surface runoff originating in close proximity to the gaging station will arrive early in the hydrograph. The timing of the arrival of the surface runoff from more distant parts of the watershed depends on the routing of water through the drainage network.

Some of the rainwater which infiltrated into the soil will move laterally to the stream systems. This pathway, which is often referred to as interflow, can be very important in agricultural lands with tile drainage systems. Chemically, this water contains much higher concentrations of certain soluble nutrients, such as nitrates, than does the surface runoff. Also, its content of total dissolved ions, as reflected in its conductivity, will be higher than the surface runoff. Generally this water will have a very low concentration of suspended sediments. The timing of the arrival of the interflow water at gaging stations will vary with the distance and pathway of water within the drainage network. This movement of water will be delayed relative to the surface water movement to the gaging station. As the hydrograph progresses at the gaging station the proportion of water derived from surface runoff

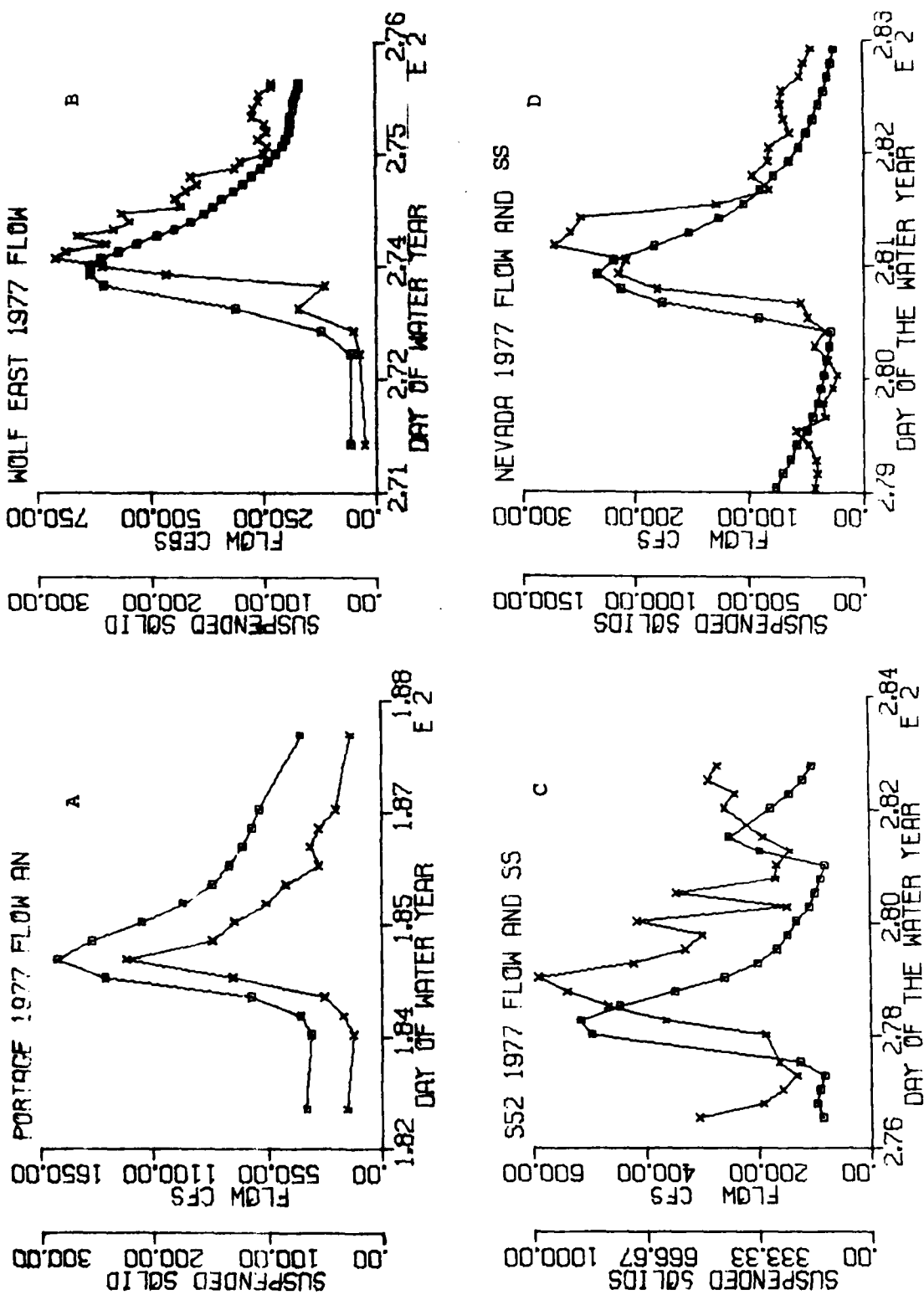


Figure 10. Examples of simultaneous (A) and trailing (B, C & D) sediment peaks during the 1977 water year at the Portage, Wolf East, Upper Sandusky and Nevada stations.

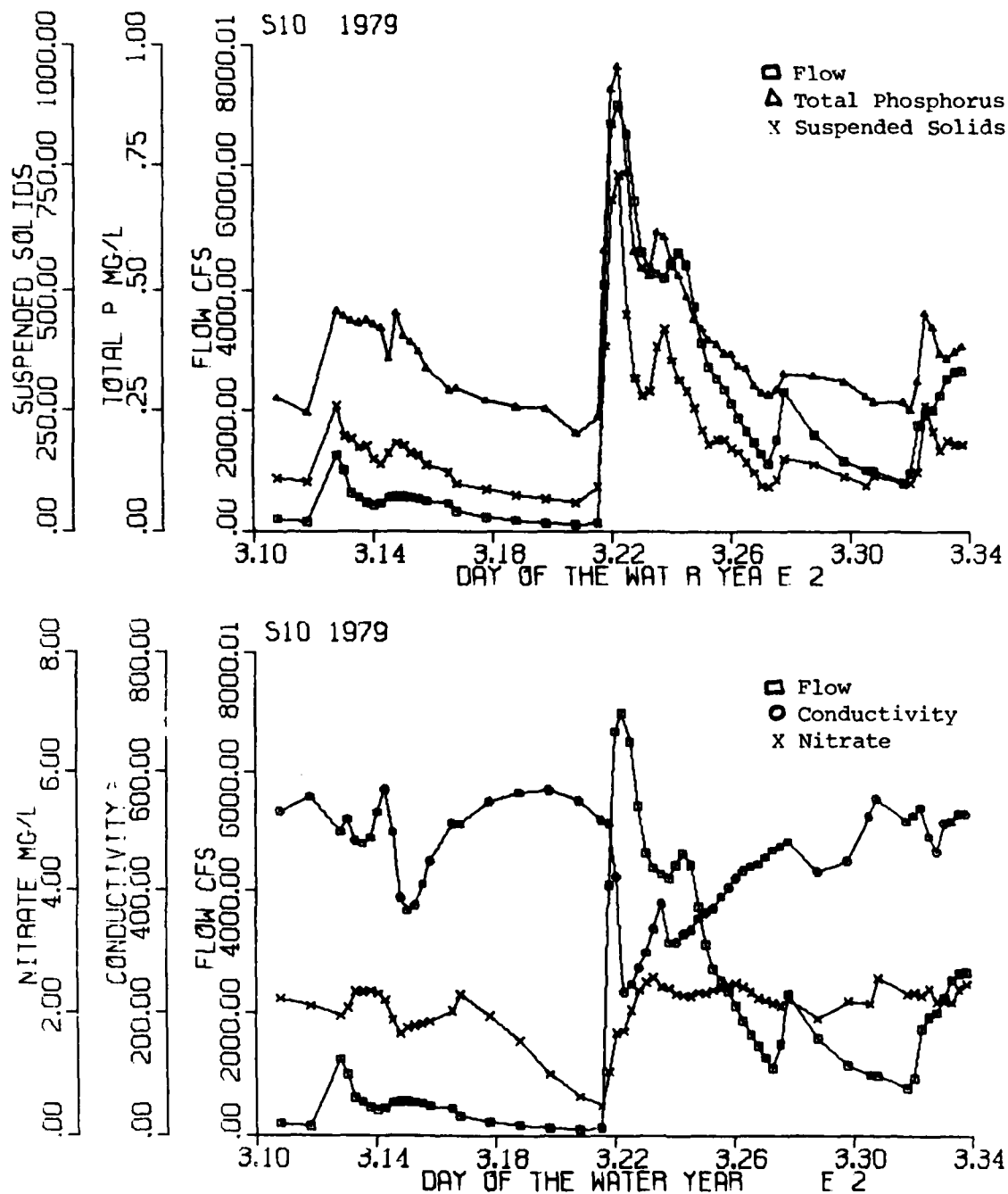


Figure 11. Compound hydrographs, sedimentgraphs and chemographs for August, 1979 runoff events at the Fremont gaging station.

relative to interflow will change, having a high proportion of surface runoff during the early portion of the hydrograph and a low proportion of surface runoff during the later stages of the runoff. This is illustrated in Figure 9g where the peak concentration of nitrates trails the peak sediment concentration and minimum conductivity.

The pattern of changes in sediment and chemical concentration at the sampling station during a hydrograph is also affected by sediment resuspension from the stream bottom, as well as by deposition of sediment both onto the stream bottom and, during larger runoff events, onto flood plains. The resuspension of sediment is related to the movement of the flood front through the drainage network. The flood front moves downstream faster than the velocity of the water. As the flow increases, the sediment carrying capacity of the water increases and sediments are picked up from the stream bottom. These resuspended sediments, along with sediments derived from surface runoff, determine the pattern of changes in suspended sediment concentration which occur at the sampling station.

Although the general sequence of peak and minimum concentrations shown in Figure 9 is common, the positions of the peaks and minimums can be shifted relative to the peak of the hydrograph. Figure 10 illustrates storms in which the peak sediment concentration is simultaneous to (10 a) or trailing (10 b, c & d) the hydrograph peak. The position of the peak concentration relative to the hydrograph is determined by the interaction of the various processes mentioned above. Trailing sediment peaks can most easily be explained by localized storms on a small portion of the watershed. The storm runoff water containing high suspended sediments enters the drainage network and initiates the propagation of a storm wave through the stream system. The sediment-laden storm water moves more slowly through the stream system and arrives at the sampling station after the peak of the storm wave has passed. In the case of advanced sediment peaks, it is probable that both resuspension of sediment and the routing of nearby surface runoff water contribute to the high sediment concentrations present early in the hydrograph. For large storms much of the water passing the stream gage during the late portions of the hydrograph may have been in storage over flood plains during which a portion of its sediment load was deposited.

Very often rainstorms closely follow one another. The associated hydrographs become superimposed giving rise to complex sediment graphs and chemographs. Figure 11 illustrates some storms with complex hydrographs and their associated complex sediment graphs and chemographs.

VARIATIONS AMONG RUNOFF EVENTS AT A SINGLE GAGING STATION

Part of the scatter present in the concentration versus flow graphs of Figure 8 is a result of the large variations in concentrations that accompany runoff events with approximately equal peak flows. This is true for storms with high, medium and low peak flows.

This variability is apparent within a set of 52 storm events for which good sampling records were available at the Upper Sandusky gaging station. In Table 28, there is listed the beginning and ending dates, the number of samples collected, the storm duration, the peak flow, the time weighted

Table 28. Summary of Storm Data at the Upper Sandusky Gaging Station

Storm No.	Starting Date Ending Date	Mean Flow Peak Flow (M ³ /sec.)	Samples Duration N, hrs.	Susp. Solids	Total P	Nitrate	Cond.
				Wt. Mean Position mg/l	Wt. Mean Position mg/l	Wt. Mean Position mg/l	Wt. Mean Position umhos
1	741207	20.93	20	92.7	0.248	6.29	477.
	741212	50.01	120.0	70.5%	55.2%	46.0%	54.2%
2	741212	27.03	35	79.3	0.210	6.92	443.
	741222	63.53	246.0	56.5%	49.6%	51.7%	51.0%
3	741223	24.32	23	113.40	0.297	6.50	421.
	741230	66.34	162.0	67.7%	65.1%	52.3%	50.3%
4	741231	15.58	25	71.20	0.160	5.03	490.
	750106	39.45	146.0	72.9%	57.2%	50.1%	49.2%
5	750107	37.29	30	223.3	0.445	4.89	367.
	750116	95.31	219.0	67.2%	59.4%	49.3%	46.0%
6	750125	16.09	12	131.3		3.57	483.
	750128	38.37	92.5	50.0%		51.7%	58.5%
7	750128	35.90	26	342.8	0.671	3.45	336.
	750204	99.79	157.8	76.4%	70.0%	44.4%	43.6%
8	750216	29.84	43	110.9		5.54	417.
	750222	73.66	139.5	61.9%		46.1%	51.4%
9	750222	56.65	36	538.5	0.495	3.42	288.
	750303	182.45	221.0	74.8%	62.8%	52.4%	44.8%
10	750304	15.30	20	136.9	0.408	4.31	496.
	750311	38.80	138.0	59.7%	62.7%	47.2%	54.2%
11	750329	14.30	18	247.3	0.422	4.23	479.
	750404	41.88	170.5	85.5%	76.9%	50.5%	45.8%
12	750830	14.12	19	444.4	0.994	2.80	365.
	750904	38.15	122.4	72.4%	67.5%	44.3%	46.7%
13	751018	4.28	19	32.8	0.370	2.50	711.
	751025	7.90	174.7	66.5%	66.0%	36.2%	51.4%
14	760208	19.81	10	131.3	0.358	2.45	400.
	760214	29.38	150.0	47.2%	34.4%	32.0%	39.8%
15	760215	83.41	20	716.7	0.957	4.12	311.
	760221	165.36	136.0	70.9%	66.4%	47.3%	48.2%
16	760221	21.27	17	235.5	0.370	3.81	431.
	760229	62.91	213.0	80.3%	68.2%	50.5%	43.0%
17	760303	27.29	24	420.1	0.720	3.25	386.
	760311	101.31	222.0	68.7%	66.3%	50.4%	46.7%
18	760319	12.89	21	328.5	0.594	2.82	493.
	760327	47.43	216.0	73.3%	68.1%	48.8%	49.6%
19	760618	5.49	18	368.7	0.707	12.41	637.
	760623	15.55	135.0	61.9%	59.8%	32.5%	51.2%
20	760707	9.17	26	726.8	1.070	4.74	440.
	760715	42.08	189.0	69.9%	67.8%	40.4%	50.3%
21	760723	11.55	31	1123.8	0.962	2.49	394.
	760728	34.41	115.5	79.4%	62.7%	44.1%	50.7%

Table 28 continued.

Storm No.	Starting Date Ending Date	Mean Flow Peak Flow (M ³ /sec.)	Samples Duration M, hrs.	Susp. Solids Wt. Mean Position mg/l	Total P Wt. Mean Position mg/l	Nitrate Wt. Mean Position mg/l	Cond. Wt. Mean Position µmhos
22	760807 760812	3.96 10.06	21 126.0	199.8 60.5%	0.621 62.0%	2.04 52.9%	531. 48.8%
23	770222 770302	26.88 90.16	26 228.0	220.5 58.1%	1.083 76.3%	2.86 35.7%	447. 56.1%
24	770317 770322	27.87 63.53	14 117.0	227.1 58.4%	0.506 54.6%	6.38 42.8%	485. 54.4%
25	770322 770401	16.0 43.75	20 273.0		0.258 52.1%	6.48 56.4%	534. 47.6%
26	770402 770410	31.12 100.04	18 213.0	215.5 69.8%	0.508 63.5%	5.22 44.0%	437. 46.7%
27	770503 770509	15.71 40.55	19 155.0	196.3 59.0%	0.423 56.9%	6.49 47.4%	539. 49.8%
28	770630 770704	8.98 29.55	16 114.0	1447.8 63.7%	1.480 56.3%	7.30 22.3%	499. 54.2%
29	770704 770708	6.18 14.60	16 102.0	563.0 37.1%	0.875 40.6%	9.35 53.2%	535. 57.7%
30	770709 770713	2.89 6.97	16 108.0	326.7 50.3%	0.599 48.3%	7.06 61.2%	546. 51.8%
31	770722 770728	5.68 21.01	25 162.0	621.7 40.9%	1.120 47.3%	2.34 21.5%	482. 58.5%
32	770805 770810	2.56 5.31	20 141.0	436.6 59.3%	0.792 50.7%	1.42 35.8%	665. 51.3%
33	771130 771205	18.05 44.71	13 117.0	176.4 67.6%	0.555 63.0%	7.02 40.3%	592. 46.7%
34	771208 771224	56.55 237.72	37 360.0	181.1 58.8%	0.390 59.3%	4.68 46.1%	423. 54.9%
35	780313 780318	96.41 197.17	21 141.0	36.9 51.9%	0.405 53.9%	2.20 47.6%	292. 56.9%
36	780518 780521	15.03 30.88	14 84.0	363.9 74.0%	0.666 65.0%		513. 48.2%
37	780524 780528	15.27 41.88	15 117.0	370.5 63.4%	0.556 52.3%	7.20 49.2%	509. 49.7%
38	780612 780615	2.50 5.78	10 93.0	554.7 82.3%	0.830 62.1%	2.63 62.3%	666. 43.8%
39	781202 781206	5.70 18.17	15 120.0	267.6 67.5%	0.962 66.8%	6.18 40.4%	689. 55.0%
40	781208 781217	4.62 26.65	14 234.0	184.7 82.1%	0.575 68.1%	7.79 48.6%	612. 47.6%
41	781231 790116	28.69 71.43	28 403.0	85.0 90.5%	0.367 63.9%	8.72 55.0%	632. 41.1%
42	790222 790301	42.72 115.12	21 114.0	193.2 66.0%	0.624 69.0%	3.03 44.4%	338. 56.6%

Table 28. continued.

Storm No.	Starting Date Ending	Mean Flow Peak Flow (M ³ /sec.)	Samples Duration N, hrs.	Susp. Solids	Total P	Nitrate	Cond.
				Wt. Mean Position mg/l	Wt. Mean Position mg/l	Wt. Mean Position mg/l	Wt. Mean Position μmhos
43	790301	42.60	32	293.3	0.517	3.83	318.
	790312	172.57	276.0	71.8%	63.9%	37.5%	42.6%
44	790402	17.39	14	230.0	0.495	7.45	523.
	790407	51.22	144.0	60.4%	58.5%	44.5%	52.5%
45	790408	26.38	10	310.9	0.466	7.35	472.
	790412	61.16	90.0	60.8%	57.9%	48.5%	51.4%
46	790412	36.37	29	902.7	1.216	4.21	324.
	790422	190.6	264.0	73.8%	65.7%	48.5%	45.6%
47	790510	5.18	15	529.5	0.906	5.54	554.
	790522	23.25	162.0	83.8%	72.6%	37.4%	46.0%
48	790523	15.38	17	71.5	0.337	24.48	625.
	790529	49.41	157.0	70.5%	56.2%	41.9%	50.7%
49	790610	6.15	13	331.5	0.452	9.19	569.
	790616	37.53	186.0	81.0%	56.1%	39.4%	48.9%
50	790709	4.76	11	364.5	0.622	5.18	533.
	790713	10.73	126.0	75.3%	45.6%	50.8%	48.7%
51	790714	4.84	9	318.3	0.722	3.56	489.
	790723	12.64	72.0	45.4%	39.9%	55.5%	56.2%
52	790913	14.19	19	295.8	0.592	2.11	409.
	790918	56.83	138.0	61.8%	59.5%	45.3%	52.4%

average flow and the flux weighted concentrations of suspended solids, total phosphorus, nitrate + nitrite nitrogen and conductivity. The table also includes a calculation of the percent of the total storm flux of suspended solids, total phosphorus, nitrate + nitrite nitrogen and conductivity which accompanied the first half of the water mass of each storm. This percentage is labeled "position" in the table.

In Figure 12, the complete hydrographs and sediment graphs for eight of the 52 storms have been plotted. To facilitate comparison of the hydrograph and sediment graphs, all of the storms have been plotted using the same scales for the concentration, flow and time axes. Storms A, B and C were large storms in terms of peak flows. The concentrations of suspended sediments in storm A were very high, in B were moderate and in C were very low. Storms D, E and F had moderate peak flows and again were accompanied respectively by high (D), medium (E) and low (F) concentrations of suspended solids. Storms G and H had very low peak flows, one of which (G) was associated with moderate suspended solids concentrations while the other (H) was associated with very low suspended solids concentrations.

The storm to storm variability present for sediment concentrations is also present for nutrients. In Figure 13 the flux weighted average concentrations of suspended solids, total phosphorus, and nitrate-nitrite N

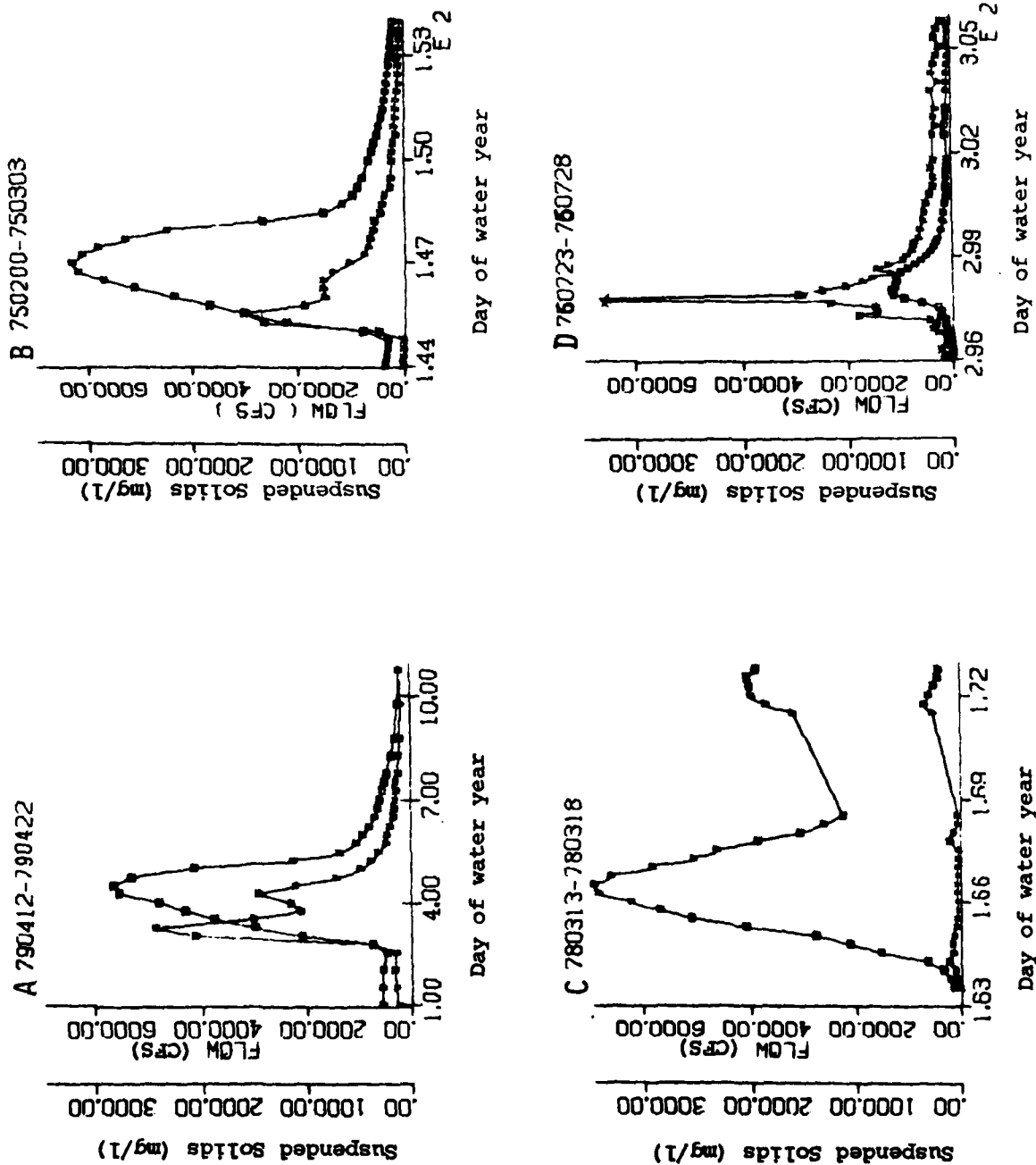


Figure 12. Variability in hydrograph-sediment graph relationships at the Upper Sandusky Gaging Station.

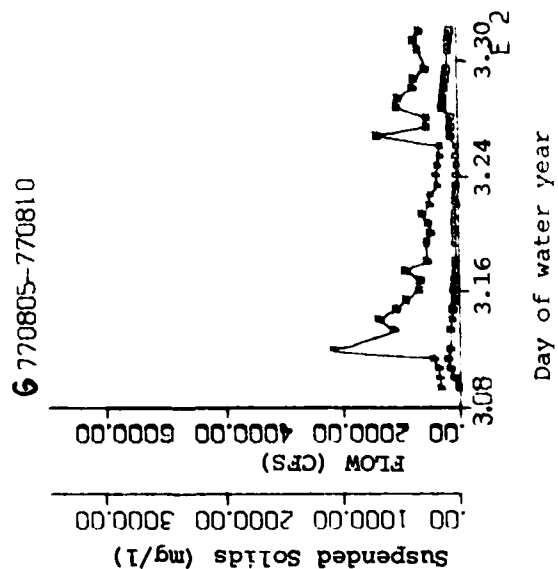
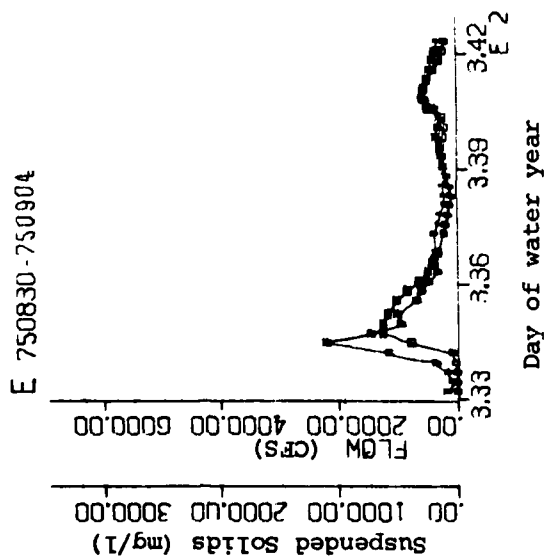
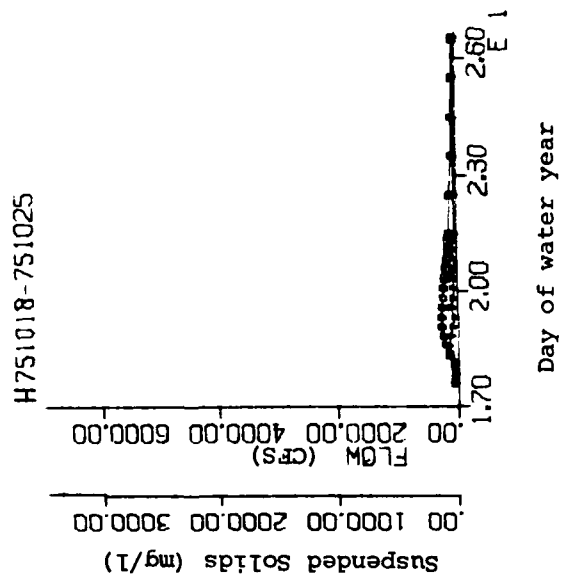
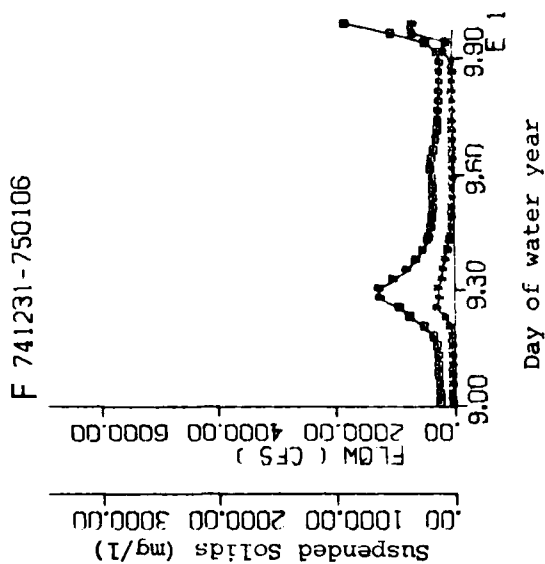


Figure 12 continued.

Upper Sandusky Storms

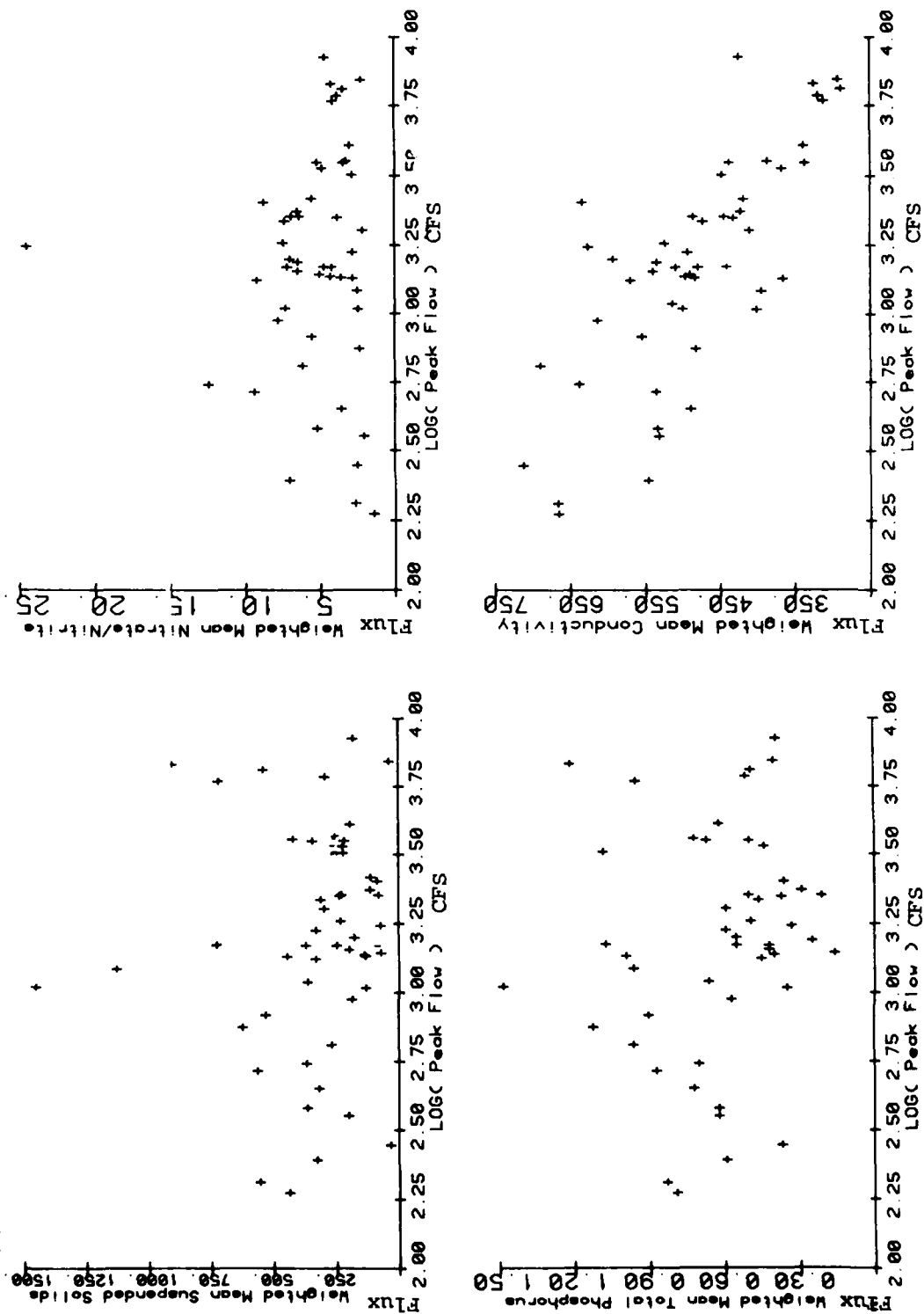


Figure 13. Variability in flux weighted mean concentrations of suspended solids, total phosphorus, nitrates and conductivity in relation to peak flows for individual storms.

along with the flux weighted conductivity are plotted as of function of the peak flow (log scale) for the set of 52 individual storms at Upper Sandusky. Again the wide variation in flux weighted concentrations for storms of similar sizes is very evident. Furthermore the scattergrams reveal no obvious trend between peak flows and flux weighted concentrations except for conductivity where average conductivity decreases as peak flows increase. Linear regressions of concentrations on peak flows, together with correlation coefficients are shown in Table 29. The correlation for conductivity is much greater than for the other parameters.

Table 29. Linear Regressions of Flux Weighted Mean Concentrations on Peak Flows for the Upper Sandusky Storm Data Set.

Parameter	Slope	Intercept	R ²	DF	Probability
Suspended Solids	-0.0522	339	0.0%	49	>> 0.1
Total Phosphorus	-0.0004	0.642	0.5%	48	>> 0.1
Nitrate-N	-0.0100	6.01	2.4%	49	>> 0.1
Conductivity	-1.37	566	50.4%	50	<< 0.001

The large variability in sediment and nutrient concentrations associated with runoff events of approximately equal size is present at all of the stream gaging stations in northwestern Ohio. The extent of this variability leads to the following conclusions:

1. Most of the time the sediment transport in the streams is less than the sediment carrying capacity of the streams at a given flow. The sediment carrying capacity would be equal to or greater than the peak sediment concentrations observed at that flow. There apparently is not a ready source of erodible sediment from stream banks or bottom that replace sediment "deficits" in surface runoff water entering the stream network. Thus programs that reduce the sediment concentration in surface runoff water should reduce the sediment yield from large river basins.
2. The interaction between watershed factors and precipitation intensity, duration, and distribution have major impacts on the concentration of sediments and nutrients present in runoff water. During the time period of the study at Upper Sandusky there were no significant changes in farming practices that would have accounted for variations in stream chemistry. The seasonal changes of ground cover associated with the prevalent rotations and tillage practices

coupled with variations in precipitation patterns are sufficient to cause the observed variations.

3. The extent of the variability illustrates the complexity of calibrating models where output includes sediment graphs and chemographs for individual storms from large watersheds. The inputs for such models must include the major variables which cause the variation in concentrations within storms with equal peak flows.
4. Studies of the sources of the variability in concentrations associated with runoff events of approximately equal size may be quite helpful both in planning sediment reduction programs and in assessing the effectiveness of programs which are implemented. Given the extent of the variability present within these 52 storms, further study of these may reveal some of the major factors affecting the concentration of materials during storm events.

VARIATIONS ASSOCIATED WITH SEASON AND RAINFALL INTENSITY

Individual Storms

One important factor influencing the concentrations of materials present during runoff events is the season of the year. In particular, those runoff events which are produced as a result of snow melt often have much lower sediment concentrations than events associated with rainfall. This is readily apparent in the data set of Upper Sandusky storm events. In Figure 14, the month in which each storm event occurred has been added to the graph of weighted mean sediment concentrations in relation to peak flow. It is evident that the flux weighted average concentrations of suspended solids are much smaller in December (12), January (1), February (2) and March (3) than for other months. This is particularly so for storms with medium and small peak flows.

Storm #48 (Table 28) provides an interesting exception to the above pattern. This storm, which occurred May 23-29, 1979, had a very low sediment concentration in relation to the spring storms of similar peak flows. This runoff event followed a series of prolonged gentle rains. In Figure 15 tracings from a recording raingage located in the watershed are shown from the above storm as well as for a storm which occurred on April 13, 1979. The latter storm had much higher sediment concentrations (Table 28, Storm #46).

Storm #48 was also accompanied by extremely high nitrate concentrations (flux weighted average = 24.48 mg/l). Apparently a high proportion of the rainfall infiltrated into the soil and reached the stream through drainage tile systems. The tile effluents have high nitrate and low suspended solids concentrations. There apparently was little surface runoff water to dilute the tile effluent.

From the standpoint of drinking water quality, periods of prolonged gentle rain deserve special attention in agricultural areas with tile drainage systems. Many of the newer pesticides have a fairly high water solubility and their behavior may parallel nitrates.

Upper Sandusky Storms

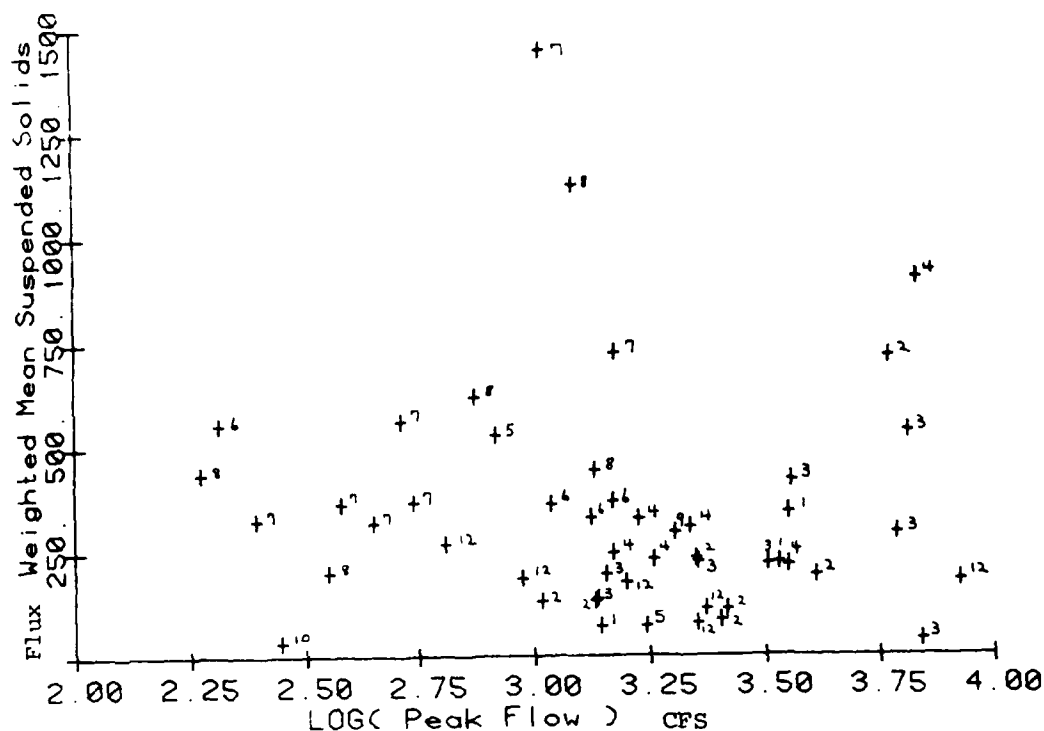


Figure 14. Flux weighted mean concentrations of suspended solids in relation to peak flow with month of occurrence marked for individual storms. (Jan. + 1, Feb. + 2, etc.)

Seasonal Sediment and Nutrient Rating Curves

Since the sediment concentrations during snow melt events are lower than during rainfall induced events, separate sediment rating curves are often produced for winter and summer conditions (Strand, 1975). These curves involve a separate plotting of sediment concentrations in relation to stream discharge for winter periods and for summer periods. Figure 16 shows such a plot for the Melmore gaging station.

In Figure 16a the sediment concentrations are plotted in relation to stream discharge while in Figure 16b sediment flux is shown in relation to stream flow for the same data. The period from December through March is taken to include the period when snow melt generated events are likely to occur. The April through November period is taken as the non-snow melt period. In this region, midwinter thaws are common and snow seldom accumulates over the entire winter. More northerly regions are characterized by single, large, snow melt events in the spring.

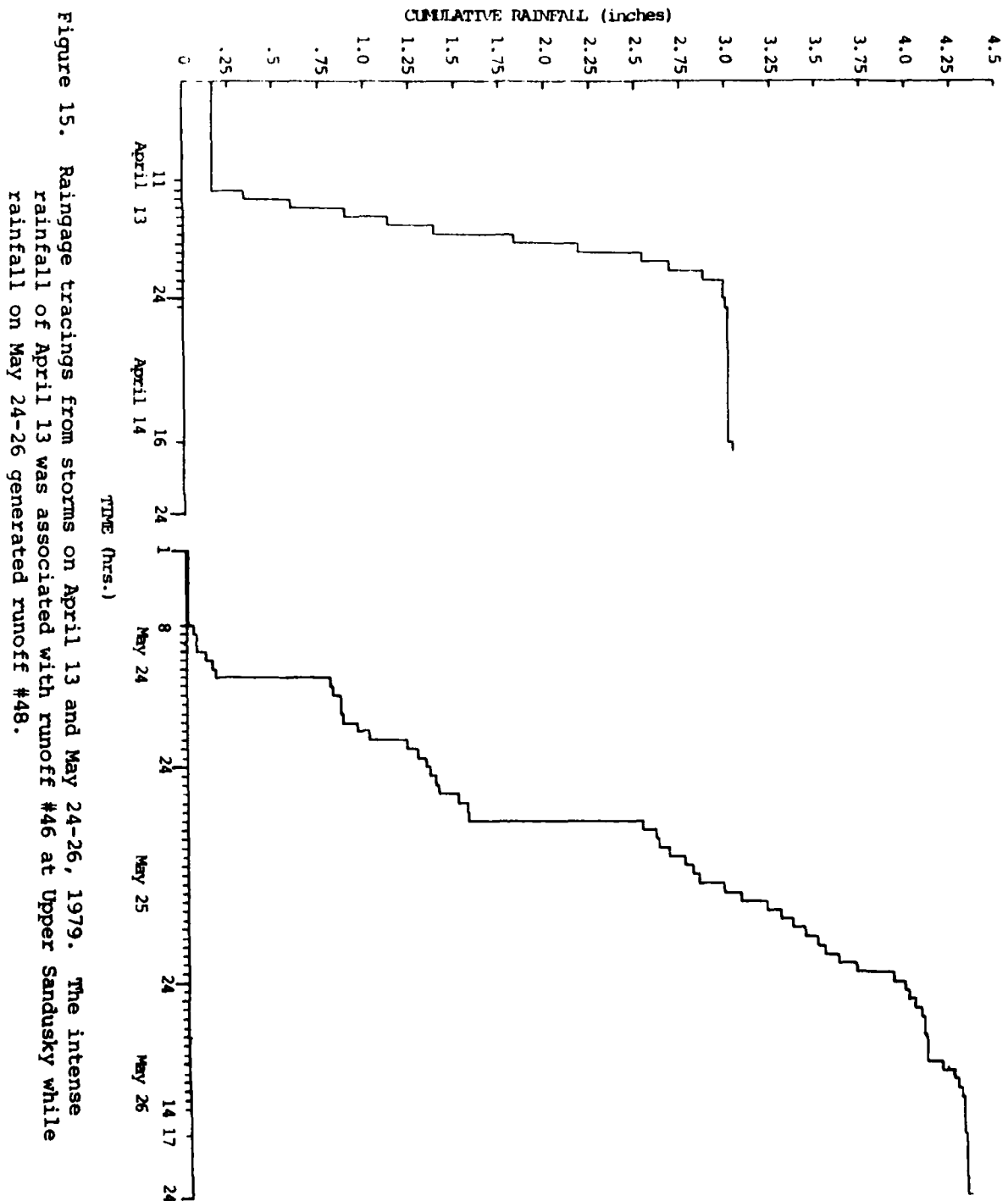


Figure 15. Rainage tracings from storms on April 13 and May 24-26, 1979. The intense rainfall of April 13 was associated with runoff #46 at Upper Sandusky while rainfall on May 24-26 generated runoff #48.

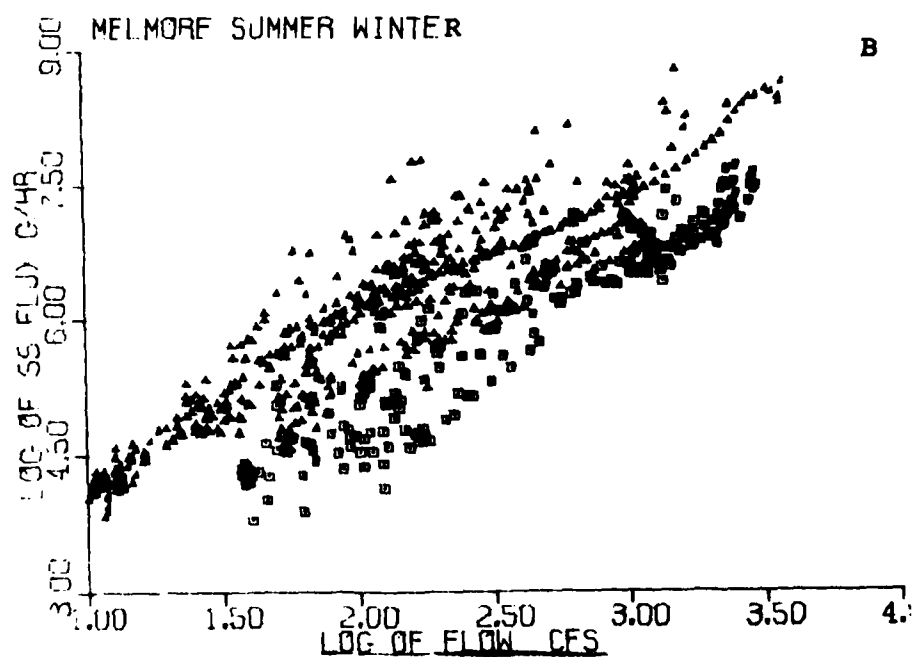
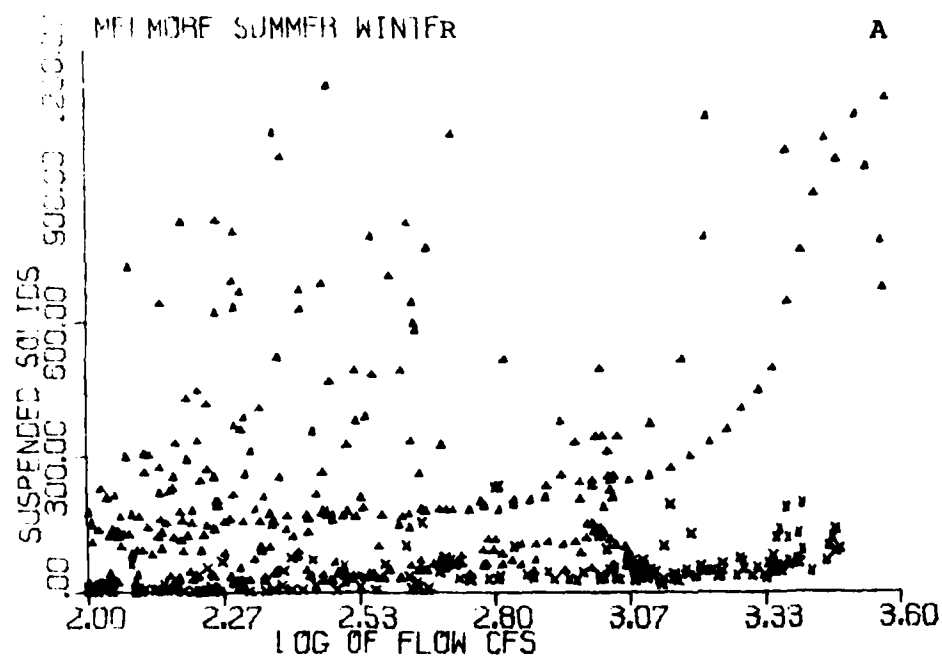


Figure 16. Seasonal sediment rating curves at the Melmore gaging station: 16A Summer (Δ) and winter (X) sediment concentrations; 16B Summer (Δ) and winter (\square) instantaneous sediment fluxes.

A convenient way of examining the seasonal aspects of concentration versus flow relationship in streams is to use the flow intervals provided within the USGS flow duration tables, as described in the methods section. All of the winter samples were sorted into the flow intervals between adjacent flow classes and within each interval the means and the standard deviations for sediment and nutrient concentrations were determined. Similar calculations were made for the samples collected during summer conditions. For each flow interval the significance of the differences between the winter and summer mean values were tested using a student t-test.

Tables 30 to 33 show the resulting means, standard deviations, and probabilities for the Melmore stream gage. In Figure 17 the summer and winter mean values are plotted according to the arithmetic midpoint of each flow interval. In the cases of suspended solids (Table 30 and Figure 17a), summer values are significantly higher than winter values over the entire range of flows. For total phosphorus summer concentrations are significantly higher than winter concentrations (Table 31 and Figure 17b) in the high and medium flow ranges. At lower flow ranges there is no significant difference in summer and winter values except at the lowest flows where winter values are statistically significantly higher than summer values.

For nitrates (Table 32 and Figure 17c) there is no statistically significant difference between winter and summer for most of the flow intervals across the entire range of flow values. For a few flow ranges, summer values were higher than winter values. During both summer and winter the highest concentrations tended to occur just below the peak flow intervals.

In the case of conductivity (Table 33 and Figure 17d) at high flows there was either no significant differences or else the summer values had higher conductivity than winter values. Over the medium and low flow intervals, the winter values for conductivity are significantly higher than the summer values. This is probably due to ice formation which concentrates the solutes in the remaining liquid water. The use of road salt may also have some effect on the elevated conductivities in the winter.

The summer and winter mean concentrations for each flow interval were calculated for sediments and nutrients for all of the transport stations. The resulting summer and winter rating tables were used to calculate loading when concentration data was lacking (see Section 7). The seasonal data for the other stations were similar to the examples for the Melmore station shown above.

ANNUAL VARIATIONS IN SEDIMENT AND NUTRIENT CONCENTRATIONS

The storm to storm and seasonal variability in sediment and nutrient concentrations described above results in significant variations in flux weighted mean concentrations of sediments and nutrients as measured on an annual basis. In Table 34, the annual flux weighted mean concentrations are shown for the twelve gaging stations. The total annual discharge according to final USGS figures is shown for each station along with the percent of the annual discharge which was monitored through the sampling program. The latter value was based on the instantaneous flows and time multipliers associated with sediment samples.

Table 30. Comparison of summer and winter suspended solids concentrations by flow intervals at the Wellmore sampling station.

Flow Class	Summer				Winter				P ¹
	N	Mean mg/l	S.D.		N	Mean mg/l	S.D.		
33-32	4	426.5	59.08		14	216.3	193.0	16	2.10851
32-31	9	957.0	1160		10	131.9	88.45	17	2.2493
31-30	38	218.3	279.2		46	130.0	93.94	82	2.0135
30-29	30	137.7	97.64		58	88.66	61.98	86	2.8730
29-28	37	225.4	219.3		38	84.13	82.83	73	3.709
28-27	49	193.4	387.6		44	77.58	53.92	91	1.96404
27-26	41	264.3	428.8		42	111.5	119.9	81	2.2223
26-25	69	175.7	185.7		38	66.03	64.82	105	3.51805
25-24	52	235.1	228.1		22	39.53	42.66	72	3.97695
24-23	46	233	222.1		22	47.69	50.50	66	3.8519
23-22	72	287.9	569.6		25	38.87	38.18	95	2.17688
22-21	61	190.6	345.7		39	28.10	27.44	98	2.92431
21-20	91	130.3	140.4		47	30.23	39.53	136	4.78179
20-19	97	93.08	112.0		41	15.33	14.79	136	4.41959
19-18	103	90.25	196.9		18	10.98	9.044	119	1.70186
18-17	102	51.35	54.7		20	7.30	10.62	120	3.57676
17-16	100	31.98	38.6		13	12.39	21.18	111	1.79036
16-15	142	21.25	19.1		5	4.38	2.066	145	1.96813
15-14	129	17.86	14.54		16	7.531	4.839	143	2.814
14-13	89	19.46	15.66		39	5.154	3.685	126	5.62551
13-12	78	15.77	8.3		11	8.236	4.850	87	2.93149
12-11	42	17.22	13.25		11	5.855	3.155	51	2.80509
11-10	15	31.61	13.66						
10-9	4	24.12	10.11						

1. Probabilities: W.S. = not significant, $\alpha < 0.10$, $\alpha\alpha < 0.05$, $\alpha\alpha\alpha < 0.01$, $\alpha\alpha\alpha\alpha < 0.001$.

Table 31. Comparison of summer and winter total phosphorus concentrations by flow intervals at the Wellmore sampling station.

Flow Class	Summer				Winter				P ¹
	N	Mean mg/l	S.D.		N	Mean mg/l	S.D.		
33-32	4	1.052	.076		14	.5203	.268	16	3.846
32-31	9	1.286	.8868		10	.359	.142	17	3.27
31-30	38	.5317	.2579		46	.383	.131	83	3.416
30-29	30	.4657	.1263		58	.324	.087	86	6.179
29-28	36	.5787	.5589		38	.315	.157	72	2.80
28-27	49	.434	.3369		44	.305	.122	91	2.40
27-26	41	.489	.3551		42	.355	.208	81	2.10
26-25	69	.407	.2170		38	.272	.115	105	3.56
25-24	52	.439	.2253		22	.216	.112	72	4.41
24-23	46	.407	.2018		21	.193	.106	65	4.57
23-22	72	.478	.5106		25	.172	.088	95	2.97
22-21	61	.360	.2652		39	.147	.085	98	4.85
21-20	92	.317	.1713		47	.137	.134	137	6.28
20-19	97	.251	.1490		41	.120	.065	136	5.41
19-18	104	.217	.1967		18	.131	.073	120	1.82
18-17	103	.189	.1335		20	.139	.076	121	1.63
17-16	106	.154	.1243		13	.204	.132	117	-1.36
16-15	142	.132	.0721		5	.176	.097	145	-1.32
15-14	126	.122	.0761		17	.149	.124	141	-1.26
14-13	91	.137	.1147		43	.094	.092	132	2.15
13-12	79	.143	.0792		13	.237	.090	90	-3.89
12-11	42	.139	.0751		11	.199	.089	51	-2.28
11-10	15	.165	.0388						
10-9	4	.225	.2059						

1. Probabilities: W.S. = not significant, $\alpha < 0.10$, $\alpha\alpha < 0.05$, $\alpha\alpha\alpha < 0.01$, $\alpha\alpha\alpha\alpha < 0.001$.

Table 32. Comparison of summer and winter NO₂-N concentrations by flow class intervals at the Melmore sampling station.

Flow Class	Summer			Winter			P ¹
	N	Mean mg/l	S.D.	N	Mean mg/l	S.D.	
33-32	4	3.522	.0806	14	3.326	1.590	NS
32-31	9	3.813	.2602	10	3.416	1.704	NS
31-30	38	7.590	6.279	46	5.011	1.898	xx
30-29	30	6.869	4.863	58	4.791	2.324	xxxx
29-28	37	6.646	3.088	38	5.916	2.494	NS
28-27	49	5.817	3.110	44	5.795	2.696	NS
27-26	41	4.791	2.787	42	5.541	2.700	NS
26-25	69	5.784	3.171	38	4.903	2.381	NS
25-24	52	7.231	4.607	22	4.465	1.828	xxxx
24-23	46	5.801	4.287	22	5.628	2.169	NS
23-22	71	5.385	4.670	25	5.223	1.989	NS
22-21	61	5.689	4.092	39	4.898	2.144	NS
21-20	91	5.610	4.086	47	4.284	1.608	xx
20-19	97	5.697	4.519	41	3.999	1.435	xx
19-18	105	4.721	3.736	18	3.618	2.057	NS
18-17	103	5.310	4.541	20	4.263	1.265	NS
17-16	106	3.441	3.260	13	4.100	.9144	NS
16-15	142	2.940	2.858	5	4.360	.7358	NS
15-14	127	2.062	1.951	17	1.915	.4816	NS
14-13	89	2.195	1.699	43	1.828	.4638	NS
13-12	79	2.017	.4936	13	2.268	.2948	x
12-11	42	2.220	.6388	11	2.156	.1416	NS
11-10	14	1.531	.6215				
10-9	4	2.617	1.096				

1. Probabilities: N.S. = not significant, x = < 0.10, xx = < 0.05, xxx = < 0.01, xxxx = < 0.001.

Table 33. Comparison of summer and winter conductivities concentrations by flow intervals at the Melmore sampling station.

Flow Class	Summer			Winter			P ¹
	N	Mean umhos	S.D.	N	Mean umhos	S.D.	
33-32	4	233.5	58.9	14	230.1	51.6	NS
32-31	9	205.6	69.13	10	276.6	129.0	NS
31-30	38	349.2	84.87	46	310.7	46.58	xx
30-29	30	354.7	64.73	58	311.7	47.16	xxxx
29-28	37	345.6	80.88	38	358.0	46.46	NS
28-27	49	375.4	62.32	44	387.6	76.88	NS
27-26	41	376.4	67.58	42	409.7	64.48	xx
26-25	69	397.9	59.78	38	408.1	84.94	NS
25-24	52	420.4	71.11	22	452.9	55.41	x
24-23	45	428.8	85.77	21	520.3	90.06	xxxx
23-22	72	410.5	92.99	25	541.1	78.68	xxxx
22-21	61	469.9	111.2	39	581.2	76.69	xxxx
21-20	93	510.3	100.1	46	621.8	71.92	xxxx
20-19	98	554.7	106.9	41	675.2	80.97	xxxx
19-18	105	575.5	99.42	17	717.1	65.61	xxxx
18-17	103	611.5	95.84	19	750.5	47.80	xxxx
17-16	106	623.8	79.75	9	749.9	38.25	xxxx
16-15	143	639.0	81.06	4	818.5	61.19	xxxx
15-14	129	630.6	64.64	16	867.7	124.5	xxxx
14-13	91	631.5	68.35	43	852	40.45	xxxx
13-12	79	617.6	35.20	13	955	78.12	xxxx
12-11	42	632.2	41.75	11	909	89.31	xxxx
11-10	15	601.9	42.85				
10-9	4	642.3	57.31				

1. Probabilities: N.S. = not significant, x = < 0.10, xx = < 0.05, xxx = < 0.01, xxxx = < 0.001.

Honey Creek Near Melmore

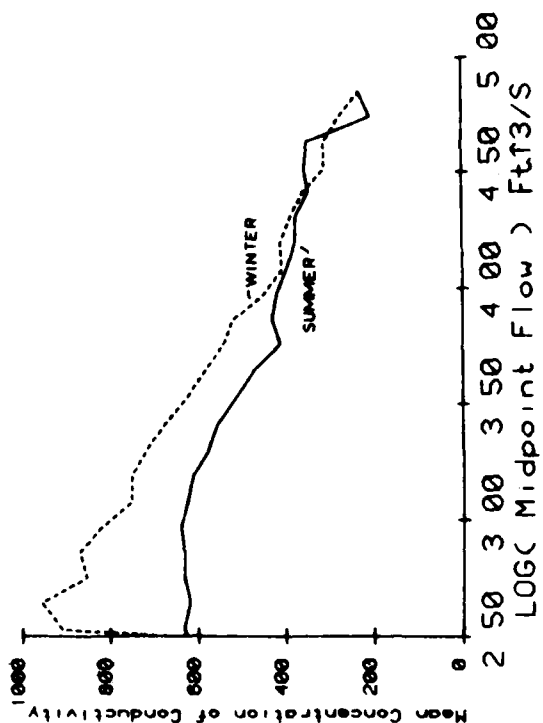
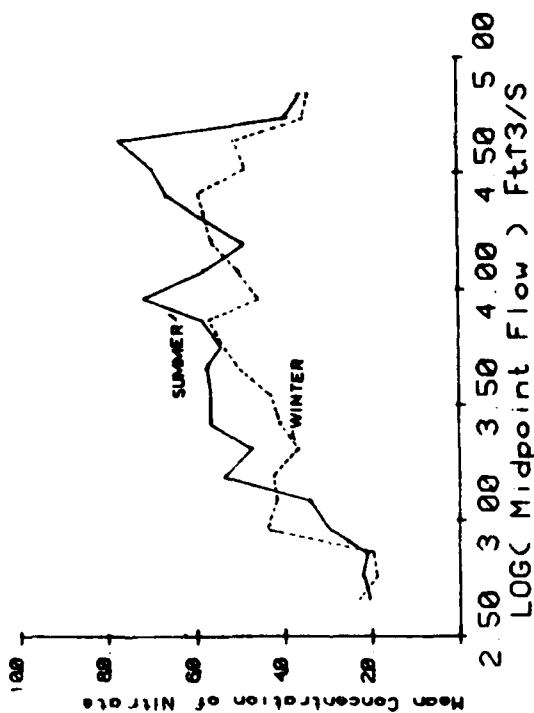
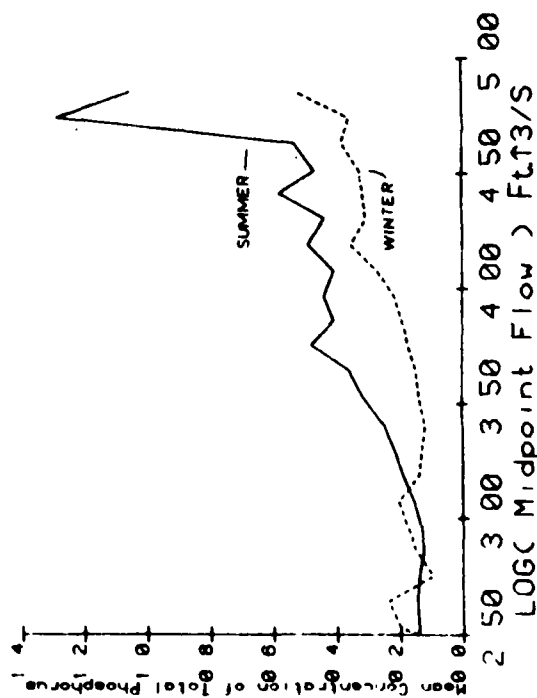
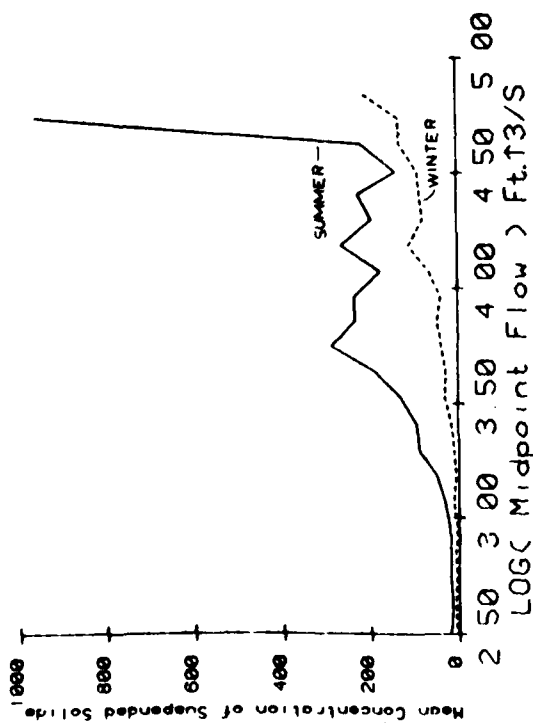


Figure 17. Summer and Winter average concentrations plotted in relation to the midpoint of the flow duration class intervals for Honey Creek at Melmore.

Table 34. Annual variations in flux weighted mean concentrations of sediments and nutrients at northwestern Ohio gaging stations.

	Water Year	Discharge 10 ⁷ m ³	Percent Monitored	Suspended Solids mg/l	Total Phosphorus mg/l	Soluble reactive Phosphorus mg/l	Nitrate Nitrogen mg/l	Conductivity umhos	TP/SS g/Kg	PP/SS ¹ g/Kg
Maumee	1975	476.3	73	279	.577	.114	6.72	522	2.07	1.66
	1976	503.5	86	315	.554	.107	3.58	503	1.76	1.42
	1977	305.3	70	404	.739	.098	6.82	554	1.83	1.59
	1978	616.6	96	138	.396	.111	4.40	448	2.87	2.06
Portage	1975	28.99	69	275	.496	.133	8.14	582	1.80	1.32
	1976	32.62	81	161	.400	.111	3.82	556	2.48	1.80
	1977	24.13	78	128	.389	.140	8.86	645	3.04	1.95
	1978	44.38	98	132	.359	.100	4.84	489	2.72	1.96
Bucyrus	1975	10.27	35	96	.441	.197	2.56	484	4.59	2.54
	1976	8.21	78	219	.596	.190	3.15	440	2.72	1.85
	1977	5.72	97	180	.673	.284	4.26	501	3.74	2.16
	1978	9.55	99	110	.460	.195	3.00	432	4.18	2.41
	1979	12.03	58	256	.604	.161	4.60	428	2.36	1.73
Nevada	1976	4.83	86	316	.451	.054	3.69	424	1.43	1.26
	1977	5.21	79	198	.276	.051	5.13	495	1.39	1.14
	1978	12.25	65	81	.226	.074	3.72	430	2.79	1.88
	1979	9.91	90	310	.522	.062	5.86	374	1.68	1.48
Upper Sandusky	1975	27.53	92	226	.402	.091	4.42	438	1.79	1.38
	1976	22.05	91	338	.570	.105	3.71	460	1.69	1.38
	1977	14.11	113	212	.646	.189	4.23	591	3.05	2.16
	1978	30.68	72	139	.431	.175	3.65	449	3.10	1.84
	1979	27.57	81	301	.613	.123	5.88	483	2.04	1.63
Tymochtee	1975	17.71	89	310	.570	.063	5.79	370	1.84	1.64
	1976	7.64	67	205	.362	.064	5.39	517	1.77	1.45
	1977	6.60	99	121	.325	.078	5.84	495	2.69	2.04
	1978	20.73	73	61	.223	.072	3.43	445	3.66	2.48
	1979	14.42	76	193	.413	.070	6.17	422	2.14	1.78
Mexico	1975	66.66		125	.335	.069	7.78	461	2.68	2.13
	1976	47.83		21	.112	.070	6.00	703	5.33	2.00
	1977	36.07		352	.657	.119	4.81	553	1.87	1.53
	1978	75.13								
	1979	63.75	6	134	.310	.072	3.01	513	2.31	1.78
Melmore	1976	6.91	121	226	.484	.053	3.71	366	2.14	1.90
	1977	7.29	112	87	.284	.092	5.82	453	3.26	2.21
	1978	14.78	109	67	.252	.083	3.78	364	3.76	2.52
	1979	15.02	105	271	.524	.081	5.17	364	1.93	1.63
Wolf West	1976	3.01	80	205	.431	.136	3.58	411	2.10	1.44
	1977	2.85	86	77	.231	.083	8.16	567	3.00	1.92
	1978	6.74	91	150	.355	.091	5.26	396	2.37	1.76
	1979	4.59	105	269	.498	.101	7.46	525	1.85	1.47
Wolf East	1976	4.40	99	346	.558	.088	5.14	497	1.61	1.36
	1977	11.50	99	77	.323	.135	4.17	661	4.19	2.44
	1978	11.21	46	194	.373	.095	5.42	552	1.92	1.43
	1979	6.27	67	272	.580	.132	4.87	464	2.13	1.65

Table 34. continued

	Water Year	Discharge 10^7 m^3	Percent Monitored	Suspended Solids mg/l	Total Phosphorus mg/l	Soluble Reactive Phosphorus mg/l	Nitrate Nitrogen mg/l	Conductivity umhos	TP/SS g/Kg	PP/SS g/Kg
Fremont	1975	103.0	67	294	.513	.067	4.99	439	1.74	1.52
	1976	77.16	54	198	.401	.072	3.82	533	2.03	1.66
	1977	62.90	93	160	.416	.106	4.96	577	2.60	1.94
	1978	139.1	83	148	.357	.075	4.12	431	2.41	1.91
	1979	108.8	83	272	.531	.104	4.87	414	1.95	1.57
Huron	1975	30.58	80	281	.403	.080	3.66	465	1.43	1.15
	1976	26.71	83	232	.293	.141	2.31	578	1.26	.66
	1977	25.35	86	279	.436	.088	5.30	515	1.56	1.25
	1978	40.48	87	119	.291	.108	2.99	556	2.44	1.54
	1979	29.55	27	289	.490	.125	5.26	581	1.70	1.26

¹Particulate phosphorus (PP) is estimated by subtracting SRP from TP.

Values differ from 100% for a variety of reasons including our use of interim flow data for hourly stages and missing data due to sampler or stage recorder malfunction. The number of samples analyzed for each parameter each year at each station has been shown in Table 25.

In the case of sediments, the ratio of the highest to the lowest annual mean value exceeds 2 at all of the stations. Total phosphorus and nitrate concentrations also show large annual variations at most of the stations while smaller variations are present for soluble reactive phosphorus and conductivity.

Comparison of the 1978 and 1979 water years is interesting in that for both years the total discharge was large and rather similar. The sediment, total phosphorus and nitrate flux weighted concentrations were much higher in 1979 than in 1978. The monthly distribution of runoff for the Fremont and the Melmore stream gages is shown in Table 25. In 1978 the December through March period accounted for 76.1% and 73.1% of the total annual discharge at the Fremont and Melmore gages. During the 1979 water year these months accounted for 45.5% and 43.7% of the annual discharge. The seasonal distribution of runoff undoubtedly accounted for the major differences in the mean annual concentrations of sediments and nutrients between 1978 and 1979.

The extent of the variations in concentrations from year to year, even when the sampling programs are based on many samples collected throughout the year, illustrates the need for long term studies to document loading of nutrients and sediments from nonpoint sources. Seasonal analysis of runoff may account for major portions of the variability but defining the seasonal concentration-flow relations may require extended studies.

VARIATIONS ASSOCIATED WITH LOCATIONS RELATIVE TO POINT SOURCES

Another factor affecting the patterns of concentrations observed at sampling stations is the position of the station relative to point source inputs. Where sampling stations are located immediately downstream from point source inputs of phosphorus, the concentration versus flow plots show increasing concentration of phosphorus as flows decrease in the low flow range. This reflects decreasing dilution of the point source inputs by the stream water. The actual concentrations observed depend on the concentrations and flow of the point source effluent in relation to the stream flow and concentration. As the sampling station is moved downstream, the phosphorus concentrations under low flow conditions are decreased due to uptake of phosphorus within the stream system, removing it from the flowing water.

During the summer of 1974, from 32 to 52 samples were collected during nonstorm conditions at each of twenty six stations along the mainstream of the Sandusky River. The mean concentrations of total and soluble reactive phosphorus are shown as a function of mile point (distance from the river mouth) in Figure 18. The effects of inputs from the Bucyrus, Upper Sandusky and Tiffin sewage treatment plants are evident. None of the plants had phosphorus removal programs in operation at that time. The decreases in phosphorus concentration below each town reflect deposition of phosphorus rather than dilution effects (Baker and Kramer, 1976).

Table 35. Comparison of Monthly Distribution of Runoff between 1978 and 1979 Water Year.

	Fremont Gage				Melmore Gage			
	1978 10^6 m^3		1979 10^6 m^3		1978 10^6 m^3		1979 10^6 m^3	
October	12.06	0.9%	4.32	0.5%	.977	0.8%	.23	0.1%
November	14.08	1.0%	5.58	0.6%	1.63	1.3%	.32	0.2%
December	305.97	22.0%	35.10	3.2%	39.27	28.0%	6.86	4.6%
January	90.56	6.5%	55.71	5.1%	12.21	1.0%	9.53	6.3%
February	36.19	2.6%	96.53	8.9%	4.51	3.6%	15.08	10.2%
March	626.64	45.0%	308.12	28.3%	58.05	41.0%	34.04	22.6%
April	209.29	15.0%	272.77	25.0%	22.54	16.3%	39.64	26.4%
May	49.64	3.5%	85.34	7.8%	4.53	3.2%	12.13	8.1%
June	22.53	1.6%	52.18	4.8%	1.49	1.1%	16.83	11.2%
July	9.23	0.7%	31.51	2.9%	.35	0.3%	3.78	2.5%
August	12.53	1.0%	96.69	8.9%	2.13	1.5%	6.86	4.5%
September	2.48	0.2%	43.75	4.0%	.779	0.7%	4.89	3.3%
Total	1391.2		1087.6		148.5		150.2	

Another effect of point source inputs which may be present deals with diurnal fluctuations in the loading rates from the plants. Figure 19a illustrates the patterns of phosphorus concentrations observed at a series of stations downstream from Bucyrus, Ohio. Three grab samples were collected each day at each station. Although the phosphorus concentrations generally decreased in a downstream direction, the pattern at the upstream stations sometimes showed highest concentrations at Kestetter Road and sometimes at Denzer Road. If samples had been collected only on 760826 at 1600 or 2100 hours one might have concluded that a source of phosphorus existed between Kestetter and Denzer Roads. Collections at other times could also have lead to similar conclusions.

The grab sampling program used to obtain the above data was supplemented by the use of automatic samplers at Kestetter, Denzer and Caldwell Roads. The samplers were used to collect samples at two hour intervals. The results of this program are shown in Figure 19b. Large diurnal variations in phosphorus concentrations were present at Kestetter Road, which is located about 0.9 km. downstream from the Bucyrus sewage treatment plant. The occurrence of

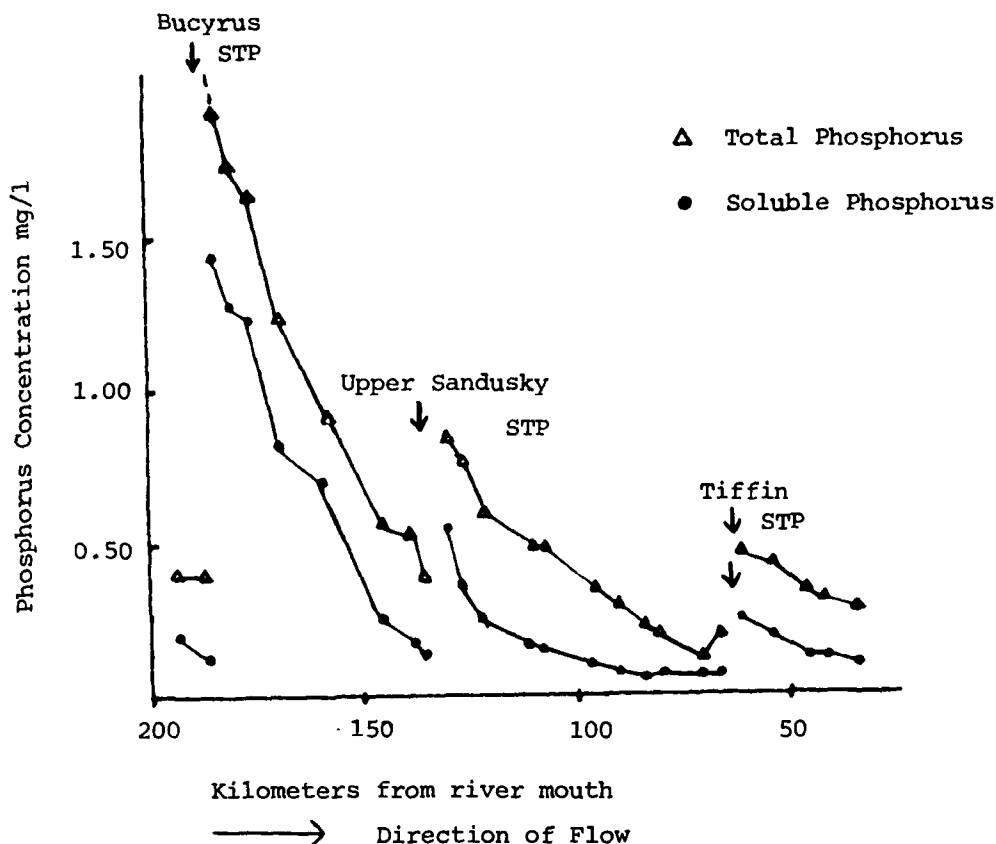


Figure 18. Profiles of mean phosphorus concentrations along the Sandusky River during June - September 1974.

higher values at Denzer Road were a consequence of the travel time between the two stations. It is apparent from a comparison of the Kestetter and Denzer Road concentrations that longitudinal mixing of the water during its passage between the two stations dampened the stream variations present at Kestetter Road. At Denzer the low concentrations were higher than the low concentrations at Kestetter Road.

The data presented in Figure 19 clearly illustrate the need for examination of possible diurnal effects at sampling stations located immediately downstream from treatment plants. Where the diurnal loading from point sources is associated with significant diurnal variations in discharge relative to stream flow, calculating material fluxes at sampling stations downstream from a stream gage are extremely difficult. The peak discharge rates at the point source input will generate wave fronts which move downstream faster than the water is flowing. For example, if the peak

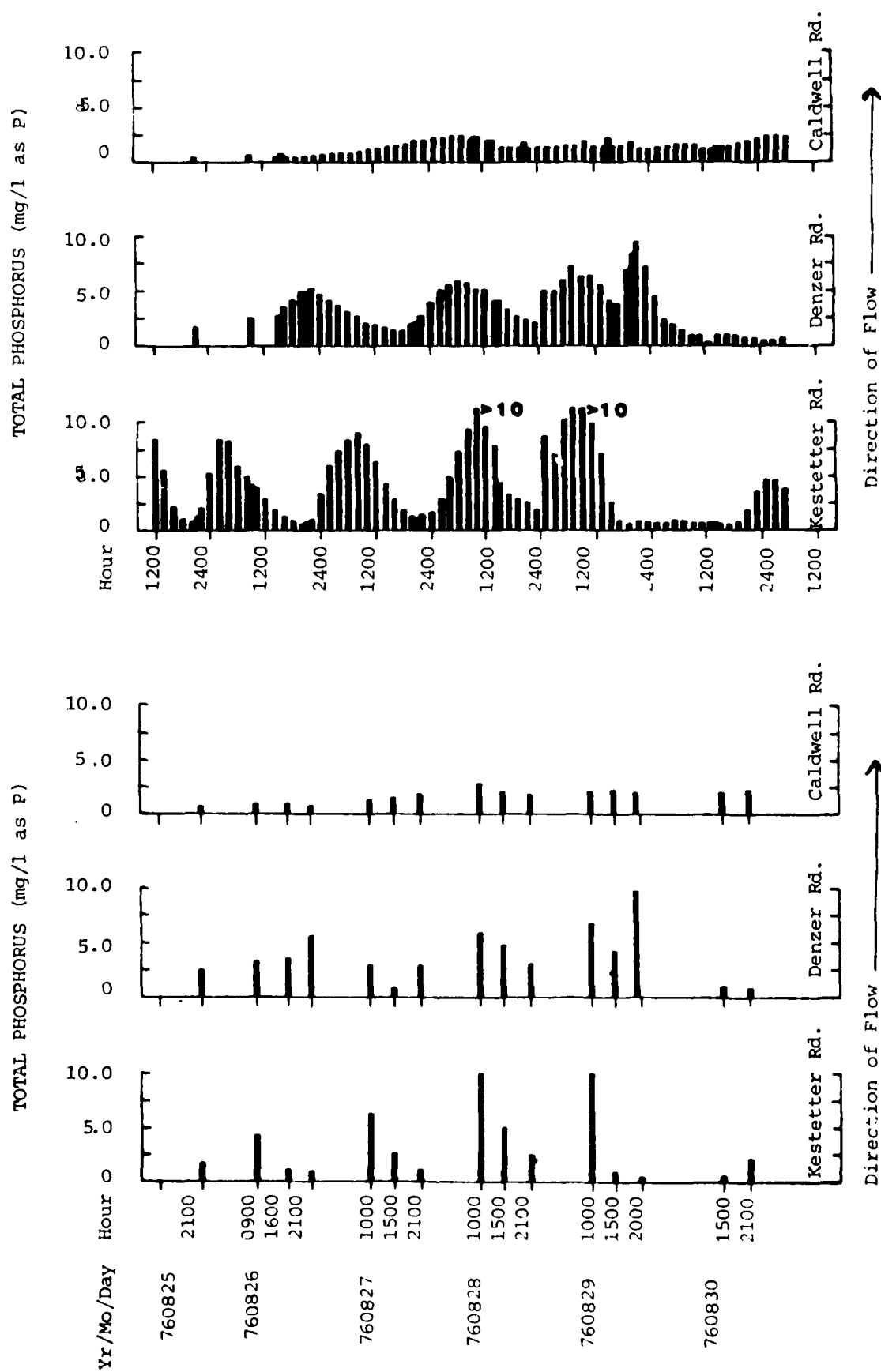


Figure 19. Comparison of phosphorus concentration profiles obtained from 3 samples per day and 12 samples per day at three bridges on the Sandusky River downstream from Bucyrus, Ohio.

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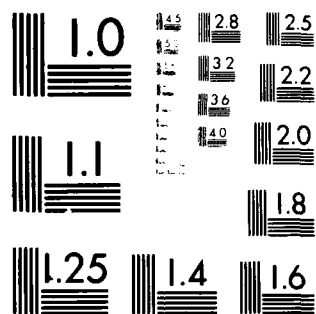
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concentrations and peak flows occurred simultaneously at Kestetter Road the peak flow would have preceeded the peak concentrations at Denzer Road, since the wave front moves downstream faster than the velocity of the water. These effects may be important when attempting to quantify processing rates. Verhoff and Baker (1980) have used the diurnal variation data to calibrate a phosphorus deposition model for the Sandusky River below Bucyrus.

CONCENTRATION EXCEEDENCY RELATIONSHIPS

An important aspect of water quality is the percentage of time that the concentrations of some parameter fall within particular ranges. Although these studies were primarily directed toward measuring tributary loading, which is dominated by high flow periods, the automatic samplers were operated continuously during both event and non-event periods. During non-event periods a single sample per day was analyzed. As described in the methods section, different time multipliers were attributed to the samples, depending on the frequency of collection of the analyzed samples. The inclusion of daily samples during low flows provides a data base which allows calculation of the time exceedency distribution of various concentrations. The calculation procedures used for producing exceedency tables are described in the methods section.

Table 36 contains concentration exceedency data for suspended solids at selected stations. For the Maumee station the data indicates that 80% of the time the suspended solids concentration exceeded 23.9 mg/l, and 1% of the time the concentration exceeded 778 mg/l. In comparing the concentration exceedency data for the various stations, it is noteworthy that the Maumee River, which is the largest of the watersheds, had much higher sediment concentrations than the other stations for much of the time. Particularly for the low range of concentrations (ie. high exceedency percentages) the concentrations exceeded fixed percentages of the time were higher for the larger rivers and tended to decrease as the watershed area decreased. At the high concentration range (ie low exceedency percentages), concentrations were highest for the watershed with the highest gross erosion rate (Nevada) and lowest for that with the lowest gross erosion (Wolf, West). It should be recalled that high suspended solid concentrations occur at high flows.

Table 37 contains concentration exceedency data for total phosphorus. High total phosphorus occurs at times of high suspended solid concentrations and also at low flows where the stations are affected by point source inputs. The concentrations of total phosphorus which were exceeded large percentages of the time were also higher in the Maumee than in the other watersheds. The total phosphorus concentrations exceeded 0.5% of the time were higher at the Portage and Nevada stations than at the Maumee. For the Maumee and Nevada stations the high total phosphorus concentrations occurred during high flows while for the Portage most of the high concentrations occurred at low flows.

The drinking water standard for nitrate-nitrogen in Ohio is 10 mg/l. At all of the stations this concentration is exceeded more than 2% of the time (Table 38). At the Portage station 10 mg/l is exceeded 5% of the time. Concentrations of 7 mg/l are exceeded more than 10% of the time at all of the stations. Since shifts to no-till agriculture in the basin may increase tile flow in proportion to surface runoff, the proportion of time nitrate

Table 36. Percentage of time the indicated concentrations of suspended solids (mg/l) were exceeded at representative gaging stations.

Percent Exceedency	Maumee	Portage	Tindall	Melmore	Wolf West	Nevada
99%	3.5 mg/l	2.1 mg/l	2.1 mg/l	1.4 mg/l	1.7 mg/l	1.3 mg/l
98%	4.0	2.9	2.9	2.3	2.3	1.9
95%	5.4	4.2	4.4	3.3	3.4	3.1
90%	10.0	5.9	6.1	4.4	4.8	4.5
80%	23.9	8.2	11.5	6.7	6.9	7.5
70%	42.0	12.2	17.5	9.4	10.2	14.3
60%	54.8	18.6	25.4	13.2	14.2	21.6
50%	67.5	27.0	34.7	19.0	18.5	29.6
40%	83.8	39.3	47.9	26.7	22.9	40.8
30%	103.0	51.8	66.9	38.8	31.6	61.4
20%	138.0	74.9	100.0	61.5	44.3	85.2
10%	221.0	134.0	176.0	123.2	78.4	142.0
5%	319.0	220.5	285.0	191.0	134.0	230.2
2%	604.0	429.0	483.0	381.0	271.0	436.0
1%	778.0	570.0	738.0	676.0	463.0	841.0
0.5%	1059.0	938.0	874.0	961.0	667.0	1436.7
Watershed area Km ²	16,395	1,109	3,240	386	171.5	271
Gross Erosion m.t./ha/yr.	6.84	5.00	8.25	6.86	4.19	9.31

Table 37. Percentage of time the indicated concentrations of total phosphorus (mg/l) were exceeded at representative gaging stations.

Percent Exceedency	Maumee	Portage	Tindall	Melmore	Wolf West	Nevada
99%	.142 mg/l	.059 mg/l	.051 mg/l	.028 mg/l	.022 mg/l	.013 mg/l
98%	.158	.073	.058	.035	.043	.018
95%	.173	.106	.073	.050	.054	.024
90%	.190	.133	.088	.067	.067	.034
80%	.221	.166	.111	.089	.092	.047
70%	.246	.197	.127	.101	.118	.062
60%	.273	.230	.142	.119	.143	.078
50%	.296	.273	.164	.140	.176	.101
40%	.321	.325	.184	.163	.208	.128
30%	.353	.401	.220	.199	.250	.154
20%	.401	.494	.287	.257	.313	.197
10%	.504	.673	.406	.366	.464	.312
5%	.685	.943	.571	.483	.601	.416
2%	.943	1.29	.848	.725	.928	.705
1%	1.128	1.49	1.080	.978	1.160	1.23
0.5%	1.480	1.72	1.279	1.24	1.290	1.58

Table 38. Percentage of time the indicated concentrations of nitrate-nitrogen (mg/l) were exceeded at representative gaging stations.

Percent Exceedency	Maumee	Portage	Tindall	Melmore	Wolf West	Nevada
99%	.01 mg/l	.02 mg/l	.02 mg/l	.480 mg/l	.040 mg/l	.059 mg/l
98%	.03	.06	.03	.770	.070	.070
95%	.13	.21	.09	.970	.110	.130
90%	.44	.47	.240	1.260	.240	.240
80%	1.45	1.07	.510	1.670	.500	.500
70%	2.01	1.70	1.190	2.020	.900	.800
60%	2.57	2.21	1.800	2.340	1.55	1.620
50%	3.20	2.93	2.560	2.820	2.66	2.230
40%	4.30	3.79	3.140	3.330	3.61	2.870
30%	5.32	4.80	4.100	3.990	4.54	3.800
20%	6.53	6.43	5.410	4.990	6.16	5.000
10%	8.02	8.69	7.200	7.380	8.21	7.200
5%	9.10	10.00	8.800	9.360	9.70	9.440
2%	10.60	11.89	10.900	13.300	11.30	13.00
1%	12.30	13.10	13.820	16.110	14.60	16.00
0.5%	13.00	14.10	16.460	18.520	16.39	18.80

Table 39. Percentage of time the indicated concentrations of total dissolved solids as represented by conductivities (umhos) were exceeded at representative gaging stations.

Percent Exceedency	Maumee	Portage	Tindall	Melmore	Wolf West	Nevada
99%	319 umhos	293 umhos	267 umhos	202 umhos	261 umhos	225 umhos
98%	348	385	307	236	320	279
95%	404	486	389	310	435	375
90%	464	585	467	369	525	460
80%	520	684	553	465	614	546
70%	558	746	623	533	665	590
60%	590	792	667	580	691	617
50%	627	834	704	607	717	647
40%	665	883	743	632		674
30%	707	930	779	659	719	702
20%	765	1017	865	689	887	731
10%	891	1146	974	736	1037	801
5%	981	1384	1077	822	1136	859
2%	1112	1460	1217	876	1331	887
1%	1239	1510	1305	919	1419	904
0.5%	1245	1554	1360	953	1462	926

concentration standards are exceeded may increase. Most of the high nitrate concentration occur in May and June.

In Table 39 concentration exceedency data for conductivity is presented. The Ohio drinking water standards for dissolved solids, when expressed as specific conductance, set a limit of 1200 umhos and a monthly average of 800 umhos. Both of the above conditions are exceeded within the major streams of northwestern Ohio. In the case of the Portage River, conductivities of 1200 are exceeded 8.0% of the time. At each station the highest conductivities occur during the winter low flow periods (see Figure 17). The relative importance of ice formation and salt use for road deicing is not known at this time.

Concentration exceedency data of the type discussed above are useful for assessing in stream water quality and the impact of proposed control programs on stream water quality. This format of presenting the data also lends itself to risk assessment considerations. In comparing the time exceedency data among the various watersheds it is also apparent that some systematic differences occur in relationship to drainage basin size. The concentrations of sediments and total phosphorus which are exceeded high percentages of the time tend to increase as drainage basin size increases. The probability of thunderstorms occurring within a basin increases as the basin size increases. Longer travel times are required for storm generated water to move through large basins. Even at low flows, the linear velocities of water would tend to increase with increasing stream order and this increased velocity could increase suspended solids transport. This is consistent with the concept of increasing transport of fine particulate organic matter in high order streams (Cummins, 1975).

SEDIMENT-PHOSPHORUS RELATIONSHIPS

A large portion of the total phosphorus transported in river systems is associated with suspended solids. Often phosphorus loading is estimated through first estimating sediment yields and then multiplying by a phosphorus-sediment ratio. The latter can be obtained from empirical determinations or the use of phosphorus enrichment ratios and soil phosphorus values.

In Table 40 the nutrient-sediment ratios as measured for the northwestern Ohio river basins using the entire data sets for each station are listed. In this case the estimates are based on the mean annual fluxes of nutrients and sediments (see Section 7) rather than on the flux weighted mean concentrations. The highest ratios of phosphorus to sediment were observed at the Bucyrus station. This station is located a short distance downstream from the Bucyrus sewage treatment plant and the high ratios observed at that station undoubtedly reflect the effect of phosphorus derived from point sources.

The most constant of the phosphorus-sediment ratios is that for the particulate phosphorus fraction. This is estimated by subtracting the soluble reactive phosphorus from the total phosphorus values. The lowest value for this ratio is found at the Nevada station, which has the highest gross erosion rates (Table 7). Nitrate ratios were also calculated although

Table 40. Nutrient-Sediment Ratios for Agricultural Watersheds
of Northwestern Ohio, 1974-1979

Gaging Station	TP/SS g/kg	OP/SS g/kg	SRP/SS g/kg	NO ₃ -N/SS g/kg
Maumee, Waterville	2.13	.48	1.65	20.3
Portage, Woodville	2.45	.73	1.72	35.9
Huron, Milan	1.64	.47	1.17	16.4
Sandusky, Fremont	2.09	.43	1.66	21.2
Sandusky, Mexico	1.79	.29	1.50	14.6
Sandusky, Upper S.	2.20	.57	1.63	16.6
Sandusky, Bucyrus	3.31	1.26	2.05	19.8
Tymochtee, Crawford	2.04	.34	1.71	25.0
Honey Cr., Melmore	2.24	.56	1.68	26.9
Broken Sword, Nevada	1.64	.25	1.39	20.0
Wolf Cr., East Br.	2.30	.65	1.65	26.0
Wolf Cr., West Br.	2.15	.55	1.61	33.6
Mean	2.17	.55	1.62	23.0
St. Dev.	.44	.26	.21	6.7

the transport of nitrates is through soluble rather than particulate forms.

One important aspect of the data on phosphorus-sediment ratios is that the values show considerable variability from year to year. This variability is shown in the data of Table 34. At the Melmore station in 1978, the TP/SS and PP/SS ratios were 3.76 and 2.52 while in 1979 the ratios were 1.93 and 1.63. Both years had similar total discharges of water. The higher phosphorus sediment ratios of 1978 were caused by much lower sediment concentration in 1978 than in 1979. As described earlier the differences in sediment concentration in 1978 and 1979 are attributable to the seasonal variations in runoff for the two years. The annual variability in nutrient-sediment ratios points out that such ratios cannot be determined on the basis of detailed one year studies. Much care should be exercised in determining these ratios for watersheds.

For individual samples there is a great amount of variability in both TP/SS and PP/SS ratios at a given station. This variability is illustrated for the Melmore station in Figure 20. The TP/SS ratios for individual samples

are plotted as a function of stream flow in Figure 20a. In Figure 20b the same data is presented with the ratios plotted as a function of suspended solids concentration. In this form it is evident that higher suspended solids concentrations are associated with lower phosphorus-sediment ratios. The same is true for particulate phosphorus ratios (Figure 20c). One possible explanation for the above would be that higher sediment concentrations may tend to have larger average particle size distributions. Since larger particles have relatively smaller surface areas, they may have less phosphorus per unit weight than finer particles.

In Figure 20 it is also evident that even at particular suspended solids concentrations, there is considerable variation in phosphorus-sediment ratios. In examining this ratio at particular sediment concentrations, it appears that the higher phosphorus-sediment ratios are associated with higher stream flows. This also could be explained in terms of particle sizes, if, at a given sediment concentration, higher stream flows are associated with lower average particule sizes. Since particle size data has not been collected in this study, the above explanations for the variations in phosphorus sediment ratios cannot be evaluated.

The variability in nutrient sediment ratios for individual samples points out the difficulties that may be encountered when attempting to measure such ratios based on the collection of a small number of samples. Since control programs aimed at reducing phosphorus loading from agricultural sources are based on erosion control programs and such programs may have different degrees of effectiveness for different particle sizes, a better understanding of nutrient-sediment ratios in relation to particle size distribution is needed. Also the relationship between the phosphorus/sediment ratios and the bioavailability of the phosphorus needs investigation.

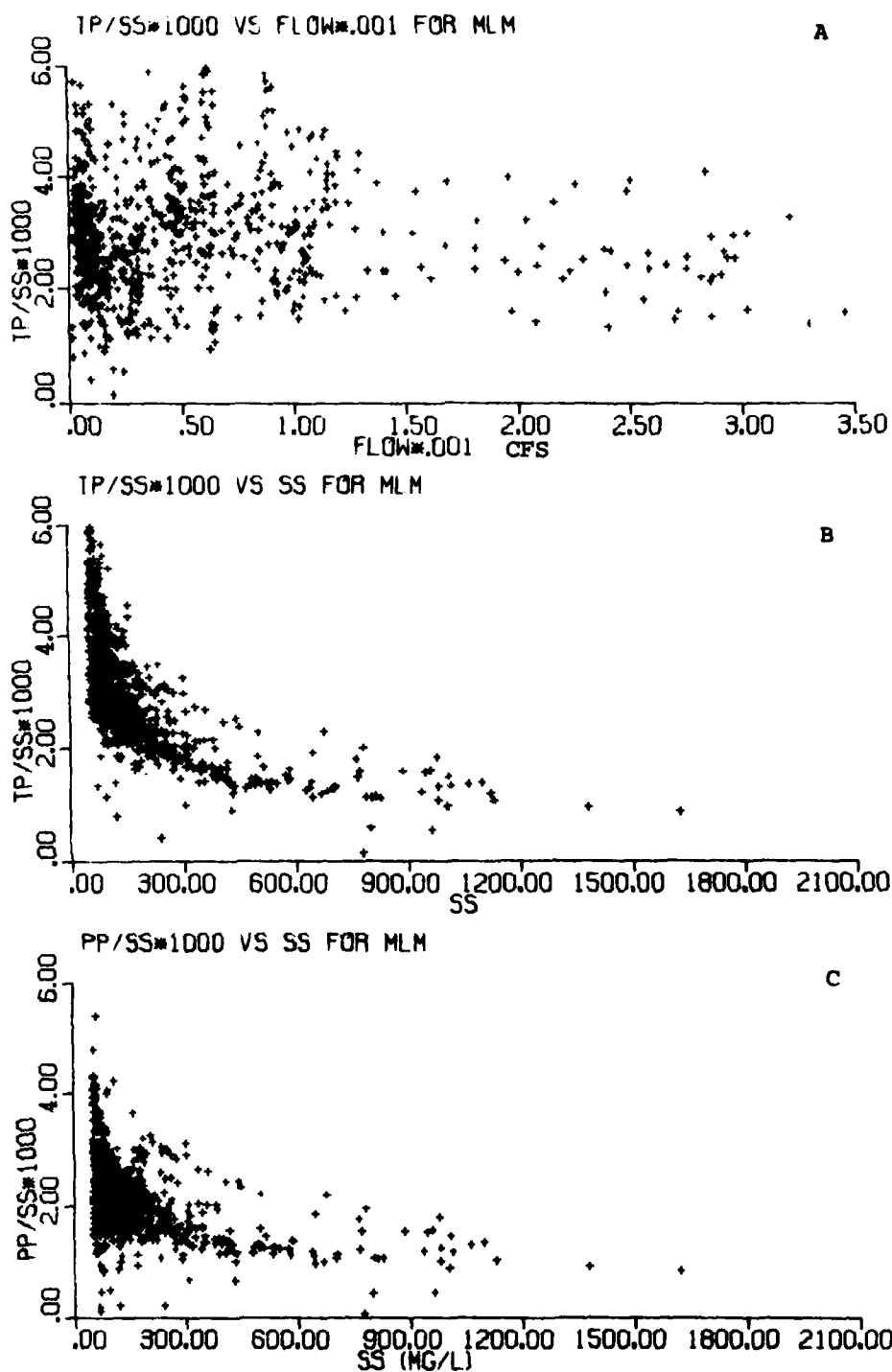


Figure 20. Phosphorus/sediment ratios ($\times 1000$) for individual samples plotted in relation to stream flow (A) and suspended sediment concentrations (B & C) for Honey Creek at Melmore.

SECTION 7

NUTRIENT AND SEDIMENT LOADING AT TRANSPORT STATIONS

In the preceeding section, various patterns of sediment and nutrient concentrations present in the rivers of northwestern Ohio were described. In this section of the report material loadings as products of concentrations and their associated stream flows will be considered.

MEAN ANNUAL LOADS OF NUTRIENTS AND SEDIMENTS

For water quality management planning information on mean annual transport of materials at various locations in a watershed is often useful. Three different methods have been used to calculate mean annual loading using the data sets available at the transport stations. These methods use either mean annual flows or flow duration tables as described below.

1. Flux Weighted Mean Concentration and Mean Annual Flow

In this procedure, the flux weighted mean concentration of each parameter at a particular station is multiplied by the mean annual discharge observed at that station for the entire period of hydrological record. This, together with appropriate conversion factors, provides mean annual loading values. A major assumption in the method is that the flux weighted mean concentration, as based on the sampling period covered by the study, is representative of the long term flux weighted concentrations characteristic of that station.

2. Flow Duration Tables and Flux Weighted Mean Concentrations For Each Flow Interval.

One way to calculate loading using flow duration tables is to calculate the flux weighted mean concentration for each flow interval, as described in Section 6. This concentration is multiplied by the mean flow of the adjacent flow classes that form the flow interval. The percent of time the flows fell into that interval is then used as the percent of a year in which flows of that size would occur. For each interval multiplying the product of the mean flow and the flux weighted mean concentration by the expected duration of these flows gives a flux for that interval. The fluxes for each flow interval can then be summed to provide a mean annual flux. The mean annual flow can also be calculated and should correspond to the published long term mean flow for the station. Table 23 provides an example of the flow duration method of calculating mean annual fluxes. A principle advantage of using the flow duration method is that it adjusts the data to the long term distribution of flows in the stream. Here the assumption is that the concentration-flow relationships within the data set are representative of long term concentration-flow relationships for the station.

3. Flow Duration Tables and Average Concentrations for Each Flow Interval

The third method we have used in calculating mean annual loading is a variation of the method described above. For each flow interval instead of calculating a flux weighted mean concentration the arithmetic mean is calculated along with the standard deviation and the standard error of the mean. Both the mean and the standard error are multiplied by the mid flow and duration so that a "loading error" estimate can be determined for each flow interval. The above loading errors for each interval were then summed to give an error estimate associated with the mean annual load. Table 24 provides an example of the calculations of mean annual loading using this procedure.

The mean annual loadings of sediments and nutrients as calculated by the three methods described above are shown in Table 41. Flux weighted mean concentrations are shown in Table 27 and mean annual flows in Table 1. Since the Nevada, Melmore, Wolf West and Wolf East stations have relatively short periods of hydrological records, mean annual discharges had to be estimated for these stations. The estimation method included comparing the discharges observed at nearby long term stations during the period of operation of the new gaging stations with the average annual discharge observed at the long term stations. The mean annual discharge at the new stations was calculated using the measured discharge at the new station and the ratio of the observed flow during the same period to the long term flow at the nearby long term stations. Flow duration tables were not used for the new stations because of the short duration of hydrological records.

In general the three methods of estimating mean annual loads gave very similar results. Also the standard error of the estimate was relatively small considering the annual variability in sediment and nutrient loadings. The standard errors as a percentage of the mean were much less for the nutrients than they were for sediments. The average loadings of the three calculated values were used in subsequent calculations of unit area loads.

UNIT AREA LOADS

In Table 42, the mean annual loads of sediments, phosphorus forms and nitrate-nitrite nitrogen are expressed on a load per unit area basis. In all cases the mean annual loads were divided by the total drainage area for the station to obtain the unit area load. Although the dominant land use in each watershed is cropland, significant percentages of other land uses do occur in each watershed (see Table 2). The phosphorus loadings were not corrected for upstream point source inputs. Such corrections are described in Section 8.

The unit area loads for phosphorus and nitrogen observed in the study watersheds represent rather high values in comparison with other areas. As part of the PLUARG study, data on unit area phosphorus loads were compiled from the PLUARG watersheds as well as from other studies in the Great Lakes region and elsewhere (Johnson, et al., 1978). A summary from that review relating unit area phosphorus yields to land use and land forms is reproduced in Table 43. The unit area yields at our river transport stations are similar to those of plowed fields on fine textured soils.

Table 41. Mean Annual Sediment and Nutrient Loading at Transport Stations

Station	Calculation Method*	Suspended Solids 10 ³ m. tons/yr.	Total Phosphorus m. tons/yr.	Dissolved Ortho Phosphorus m. tons/yr.	Nitrate-Nitrite-N m. tons/yr.
Maumee	1	1,043	2,224	500.1	21,200
	2	981	2,131	491.0	21,500
	3	1,087 ± 10.3%	2,237 ± 6.1%	479.0 ± 5.1%	22,000 ± 5.3%
	Ave.	1,037	2,200	490	21,600
Portage	1	45.6	111.7	33.1	1,640
	2	41.3	103.4	33.3	1,690
	3	47.3 ± 18.5%	108.4 ± 7.2%	34.6 ± 6.2%	1,710 ± 6.2%
	Ave.	44.7	108	33.7	1,680
Tindall	1	185	386.4	79.3	3,933
	2	156	335.5	75.1	4,164
	3	164 ± 11.9%	343.8 ± 6.4%	75.1 ± 6.1%	-----
	Ave.	168	355	76.5	4,050
Huron	1	58.9	97.0	27.9	967
	2	53.4	97.8	28.1	971
	3	57.9 ± 18%	100.5 ± 10.3%	27.2 ± 8.5%	1,010 ± 8.6%
	Ave.	56.7	98.4	27.7	983
Bucyrus	1	11.1	36.9	14.1	259
	2	13.0	45.2	18.6	261
	3	13.3 ± 13.4%	45.6 ± 7.5%	18.4 ± 7.1%	277 ± 8.3%
	Ave.	12.5	42.6	17.0	266
Upper Sandusky	1	50.8	111.9	29.0	842
	2	45.2	109.5	30.6	883
	3	50.7 ± 11.8%	113.5 ± 6.3%	30.5 ± 5.5%	914 ± 4.5%
	Ave.	48.9	112	30.0	880
Tymochtee	1	31.3	64.0	10.3	782
	2	29.8	61.6	10.4	795
	3	31.9 ± 13.2%	63.2 ± 7.5%	10.5 ± 5.5%	814 ± 6.0%
	Ave.	31.0	62.9	10.5	797
Mexico	1	123.	221.	36.1	1,804
	2	124	232	47.1	2,688
	3	141 ± 18.8%	250 ± 10.6%	43.9 ± 7.4%	2,853 ± 7.3%
	Ave.	129	234	42.4	2,450
Nevada	1	18.9	31.1	4.71	376
Malmore	1	18.9	42.2	10.56	507
Wolf West	1	8.18	17.6	4.46	274
Wolf East	1	12.9	29.8	8.42	336

*Calculation Methods: 1. Flux weighted mean concentration times mean annual flow; 2. Flow duration table and flux weighted mean concentration per flow interval; 3. Flow duration table and average concentration per interval plus or minus standard error of the estimate.

Table 42. Unit area yields of sediments and nutrients for Northwestern Ohio agricultural watersheds

Gaging Station	Area Km ²	Suspended Sediment Tons/ha	Total Phosph kg/ha	Soluble Reactive Phosph kg/ha	NO ₃ -NO ₂ Nitrogen kg/ha
Maumee	16,395	.63	1.34	.30	13.1
Portage	1,109	.40	.97	.30	15.1
Huron	961	.59	1.02	.29	10.2
Fremont	3,240	.52	1.10	.24	12.5
Mexico	2,005	.65	1.17	.21	12.2
Upper Sandusky	772	.63	1.45	.39	11.4
Bucyrus	230	.54	1.85	.74	11.5
Crawford	593	.52	1.06	.18	13.4
Honey	386	.49	1.09	.27	13.1
Nevada	217	.87	1.43	.22	17.3
Wolf, East	213	.61	1.40	.39	15.8
Wolf, West	171.5	.48	1.02	.26	16.0

kg/ha/yr

Table 43. Total Phosphorus Unit Load/by Land Use and Land Form (in U.S.A.)*

Form Use	Fine Textured		Medium Textured		Coarse Textured	
	Level	Sloping	Level	Sloping	Level	Sloping
Plowed fields	1.06	1.25	.87	.87	.23	.63
Grassland	.23	.23	.10	.10	.10	.10
Dairy (pasture)	.40	.63	.23	.23	.10	.10
Brush	.23	.23	.23	.23	.23	.23
Orchard/ truck crops	1.25	1.25	1.25	1.25	1.25	1.25
Forest	.10	.10	.10	.10	.10	.10

*From Johnson, M. G., et al., Management Information Base and Overview Modelling, 1978.

Uttormark, et al. (1974) reviewed 19 studies on nutrient transport from agricultural lands by streamflow and found the following ranges and means:

	Total-N kg/ha/yr	Total-P kg/ha/yr
max	13.0	2.3
min	1.2	0.03
ave	5.1	.38

For seven of the northwestern Ohio watersheds (Table 42) the export of nitrate nitrogen exceeded the maximum total nitrogen export listed in the studies reviewed by Uttormark. Also the unit area phosphorus yields in northwestern Ohio are three times higher than the mean loads from the studies reviewed by Uttormark.

In a nationwide survey of the relationships between nonpoint sources and stream nutrient levels, Omernik (1977) noted the following mean values for phosphorus and nitrogen export:

	Ortho- phosphorus kg/ha/yr	Total Phosphorus kg/ha/yr	Inorganic Nitrogen kg/ha/yr	Total Nitrogen kg/ha/yr
<u>> 75% Agriculture</u>	0.094	0.255	3.26	5.54
<u>> 90% Agriculture</u>	0.118	0.266	7.81	9.54

The total phosphorus export rates for the northwestern Ohio watersheds (Table 42) are about four times higher than the mean values in the nationwide survey. Likewise, the orthophosphorus and inorganic nitrogen export rates are two - three times higher than the mean value in the nationwide survey.

ANNUAL VARIATIONS IN NUTRIENT AND SEDIMENT LOADING

One of the objectives of this study was to determine the extent of annual variations in nutrient and sediment export from the study watersheds. A preliminary estimate of the annual loading for each water year can be obtained by using the flux summary programs described in Section 5 and selecting for the water year dates. However, in any year there is generally a significant amount of missing data as noted in Table 25.

Erroneous or missing stage data and missing chemical analysis data generally result in the need to correct the preliminary loading calculations. These corrections are made as follows:

1) Erroneous Stage Data

The formation of ice jams occasionally results in high stage readings which are not associated with high flows. The hourly stage data from the USGS preliminary reports are not corrected for ice jam effects, and thus when these stages are entered into the chemical data sets, the associated flows are too large. The final flow data as presented in the Water Resources Data for Ohio for each water year presents corrected mean daily flows and both monthly and yearly total flows.

A computer program is used to compare the total flows, summed from the chemical data sets for each month, with the U.S. Geological Survey's reported monthly flows. Table 44 shows a sample printout from the program. The ratio of the USGS flow values to the calculated flow from the chemical data sets is listed along with the number of samples collected, the total hours monitored and the weighted mean concentration. For any month when the ratio is less than one, the flow data from the chemical data set is compared with the mean daily flows from the USGS records and corrections are made in our data archives to bring the flows into agreement with the USGS values.

2) Missing Stage Data

Malfunctions in the stage measuring and recording equipment occasionally occur and result in gaps in the stage data. The automatic samplers continue operation, the samples are analyzed and the results entered into the computer. Thus concentration data is available but flow data at the specific times of sample collection is not available. In such cases the monthly summary tables show higher USGS flows than the calculated flows.

The USGS estimates daily flows during these gaps by comparison with nearby gaging stations. These estimates are published in the Water Resources Data and are indistinguishable from the mean daily flows calculated from hourly stage data. In order to calculate fluxes for these time periods, the mean daily flows from the Water Resources data are entered into our archive data set and used in conjunction with the measured chemical concentrations.

3) Missing Chemical Data

Gaps in the chemical records are generally caused by pump failures at the gaging stations or by problems with the automatic samplers. In these cases, the archive sets contain neither stage (and flow) data nor chemical data. If the period of missing data includes significant flows, then the monthly summaries again show higher USGS flows than the calculated flows associated with the chemical data set. In this case corrections are made using the mean daily flow from the USGS records and seasonal concentration/flow relationship for each station and parameter as described in Section 6.

Table 44. Sample printout of monthly flux and flow summaries used for identifying and correcting erroneous or missing flow and concentration data.

ATEP QUALITY LAB HEIDELBERG COLLEGE									
THU, JUL 24 1980									
STATION:UPPER SANDUSKY RIVER									
PARAMETER:TP									
BEGINNING DATE:TIME:7510010600									
ENDING DATE:TIME:7609301900									
MONTH	N	WT MEAN MG/L	CUM TIME HRS	OPS FLOW M**3	USGS FLOW M**3	FLOW RATIO	CBS FLOW METRIC TONS	CALC FLOW METRIC TONS	
OCT.	55.00	.3106	732.2	.5236E 07	.4784E 07	.9137	1.626	1.486	
NOV.	12.00	.3215	246.1	.8848E 06	.2914E 07	3.294	.2845	.9370	
DEC.	23.00	.3199	375.5	.8039E 07	.2145E 08	2.668	2.572	6.862	
JAN.	36.00	.3232	510.2	.3970E 08	.4572E 08	1.152	12.83	14.78	
FEB.	59.00	.7022	634.0	.7057E 08	.6747E 08	.9560	49.55	47.38	
MAR.	61.00	.5929	750.0	.3965E 08	.3676E 08	.9271	23.51	21.60	
APR.	33.00	.1641	696.0	.8057E 07	.8122E 07	1.008	1.322	1.330	
MAY	28.00	.5873	585.0	.3982E 07	.4720E 07	1.185	2.339	2.772	
JUNE	89.00	.7330	723.0	.1115E 08	.1031E 08	.9252	8.170	7.559	
JULY	127.0	.9145	741.0	.1350E 08	.1245E 08	.9224	12.35	11.39	
AUG.	95.00	.5555	753.0	.4722E 07	.4600E 07	.9743	2.623	2.500	
SEP.	33.00	.4264	573.0	.1091E 07	.1171E 07	1.074	.4652	.4995	----
	653.0	.5695	7119.	.2044E 09	.2205E 09		117.6	119.3	----

Table 45. Annual variability in sediment and nutrient export from selected northwestern Ohio rivers.

Station	Water Year	USGS Discharge M ³	Suspended Solids		Total Phosphorus		Soluble Reactive Phosphorus		Nitrate-Nitrite Nitrogen		TP/SS g/kg.
			Conc. mg/l	Load tonnes	Conc. mg/l	Load tonnes	Conc. mg/l	Load tonnes	Conc. mg/l	Load tonnes	
Portage	1975	28.99	213	61,740	.391	113.3	.128	37.29	7.45	2158	1.83
	1976	32.62	155	50,550	.381	124.3	.114	37.32	4.20	1371	2.46
	1977	24.13	161	38,930	.410	98.8	.137	33.03	7.94	1916	2.54
	1978	44.38	131	58,340	.367	162.8	.107	47.51	4.96	2200	2.79
Fremont	1975	103.0	293	302,200	.407	418.9	.068	70.42	4.57	4709	1.39
	1976	77.16	161	124,000	.516	398.9	.064	49.67	3.39	2621	3.22
	1977	62.90	146	91,560	.409	257.5	.104	65.76	4.98	3135	2.81
	1978	139.1	139	193,500	.333	463.4	.084	116.9	3.56	4958	2.39
	1979	108.8	263	285,500	.518	563.4	.103	112.2	5.16	5615	1.97
Tymochtee	1975	17.71	282	50,010	.526	93.3	.061	10.87	5.49	972.6	1.86
	1976	7.64	148	11,320	.278	21.3	-----		4.37	334.1	1.88
	1977	6.60	126	8,342	.334	22.1	.079	5.20	6.16	406.8	2.65
	1978	20.73	64	13,180	.207	42.9	.063	12.96	3.10	641.7	3.25
	1979	14.42	192	27,720	.411	59.3	.072	10.34	5.88	848.5	2.13
Malmore	1976*	6.91	276	19,090	.588	40.69	.080	5.53	4.56	315.1	2.13
	1977	7.29	105	7,677	.335	24.41	.115	8.33	6.78	494.8	3.18
	1978	14.78	74	11,000	.276	40.81	.090	13.35	4.14	611.3	3.71
	1979	15.02	287	43,115	.586	88.00	.093	13.96	5.93	890.5	2.04

*February through September only.

The above methods for correcting annual loading estimates have been applied to the four stations shown in Table 45. The Table includes a listing of the total flow observed by the USGS each year, and the estimated load and the flux weighted mean concentration for suspended solids, total phosphorus, soluble phosphorus, and nitrate plus nitrite nitrogen.

In examining the data on annual variations in sediment and nutrient export, the following features are evident:

1. Both sediments and nutrients are characterized by large annual variations in export. The ratios of the high annual yields to the low annual yield observed during the 3 - 5 year periods at the four stations are shown in Table 46. The largest variations were for suspended solids but even the soluble nutrients showed considerable variation.

Table 46. Ratio of high annual yield to low annual yield.

Station	Years	SS	TP	SRP	Nitrate-N
Portage	4	1.58	1.65	1.42	1.60
Fremont	5	3.30	2.19	2.35	2.14
Tymochtee	5	5.99	4.38	2.49	2.91
Melmore	3	5.613	3.61	1.68	1.80

2. Annual sediment yields are not directly proportional to annual discharge. For example at Fremont the 1978 discharge was 28% higher than the 1979 discharge but the sediment export in 1978 was 32% lower than the 1979 sediment export. The flux weighted mean concentration of sediment in 1978 was 139 mg/l while in 1979 it was 263 mg/l. Large variations in annual flux weighted mean concentrations occur at each station and the values do not correlate with flow. At Tymochtee the highest annual discharge (1978) had the lowest average sediment concentration (64 mg/l) while the second highest annual discharge (1975) had the highest average sediment concentration (282 mg/l). As discussed in the previous section the major factor affecting this variability is probably the proportion of the annual runoff that occurs during winter months.
3. Annual yields of total and particulate phosphorus are not directly proportional to annual yields of suspended solids. This is reflected in the rather wide variations in the ratios of total and particulate phosphorus yields to suspended solids yields (Table 45). As discussed in the previous section, the phosphorus to sediment ratios decrease with increasing sediment concentration. This is illustrated in Figure 21 where the TP/SS ratios of the annual yield are plotted as a function of annual flux weighted mean concentrations of suspended solids.

FLUX EXCEEDENCY RELATIONSHIPS

The range in fluxes of substances at a particular station greatly exceeds the range in concentrations. One way to characterize the range in fluxes is to calculate the percentage of time a given flux is exceeded. The computer programs for calculating flux exceedency are described in Section 5.

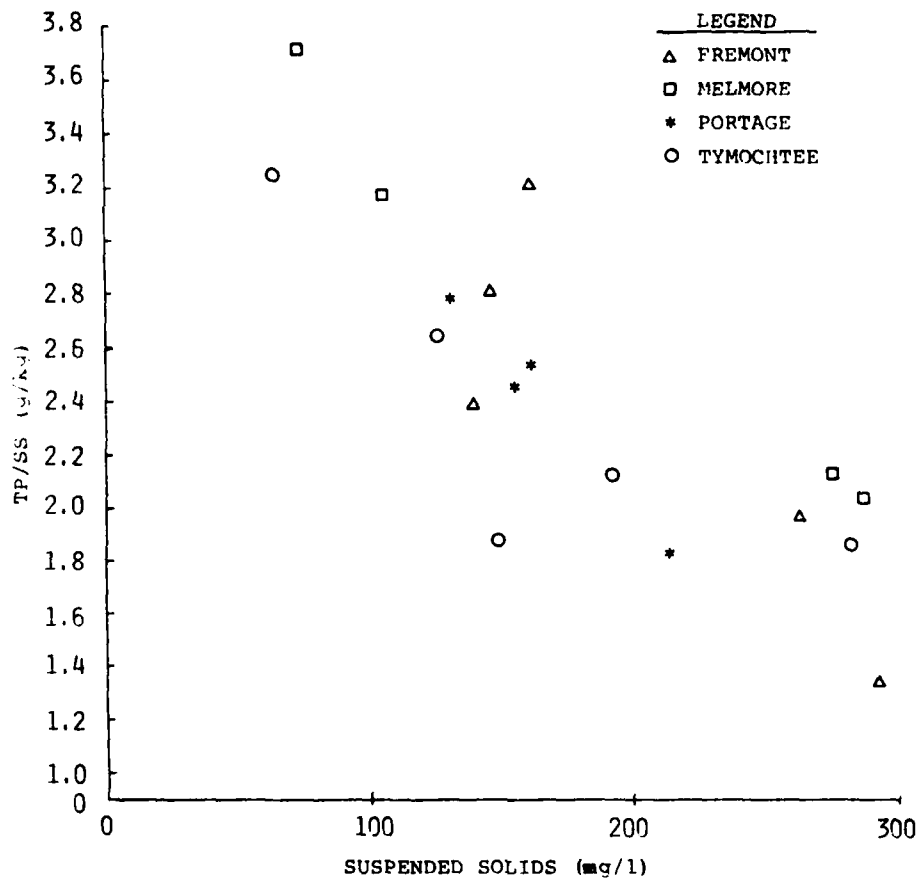


Figure 21. Annual variations in the ratio of total phosphorus export to suspended sediment export in relation to annual flux weighted suspended solids concentration.

Table 47 provides an example of a flux exceedency table for the Fremont Station on the Sandusky River. The time exceedencies are based on approximately 30,000 hours of sampling data at the station during which time 2150 discreet samples were collected and analyzed. The wide range of fluxes is evident in the data.

The importance of the high flux and high flow values in terms of total transport at the sampling stations is shown in Table 48. The information in Table 48 was summarized from both flux exceedency and flow exceedency tables in which the cumulative percent of the total flux was also listed (see Table 20 and 21). The data in Table 48 indicate, for example, that for the Maumee River at Waterville the flows exceeded 1% of the time accounted for 11.7% of the total discharge, 13.6% of the suspended solids flux, 12.9% of the TP flux, 10% of the SRP flux and 7.6% of the dissolved solid flux. The suspended

Table 47. Flux exceedency values for suspended solids, total phosphorus and soluble reactive phosphorus at the Fremont gaging station.

Percent Exceedency	Suspended Solids kg/hr	Total Phosphorus kg/hr	Soluble Reactive P kg/hr
99%	20.9	.285	.008
98	35.2	.355	.022
95	49.6	.467	.082
90	78.4	.709	.158
80	134.9	1.257	.337
70	235.5	1.973	.675
60	410.5	2.844	1.109
50	814.8	3.991	1.764
40	1,596	6.119	2.818
30	3,650	12.78	4.714
20	10,220	30.99	9.939
10	42,970	93.61	28.65
5	125,600	276.9	53.68
2	320,700	653.1	111.2
1	496,700	991.4	148.6
0.5	914,400	1515	244.0
0.1	1,341,000	2140	389.0

solids fluxes exceeded 1% of the time accounted for 30.8% of the suspended solids flux, the TP fluxes exceeded 1% of the time accounted for 20.9% of the TP flux, the SRP fluxes exceeded 1% of the time accounted for 13.1% of the SPP flux and the "conductivity" fluxes exceeded 1% of the time accounted for 8.7% of the total dissolved solids flux.

The differences between the percentages of the total fluxes accounted for by the flows and fluxes exceeded 1% of the time are greatest for suspended solids and least for total dissolved solids. It is evident at all of the stations that for suspended solids peak flows cannot account for the peak fluxes.

Table 48. Percent of total flux accounted for by fluxes associated with flows and fluxes exceeded fixed percentages of time.

Percent of total monitored flux during 1974-79 water years										
Percent Exceedency (Time)	Discharge	SS		TP		SRP		TDS*		
		Flow	Flux	Flow	Flux	Flow	Flux	Flow	Flux	
Maumee										
1%	11.7%	13.6%	30.8%	12.9%	20.9%	10.0%	13.1%	7.6	8.7%	
2%	20.6%	27.8%	46.1%	24.8%	33.3%	17.8%	21.9%	14.3	15.4%	
5%	39.2%	61.5%	70.0%	52.6%	56.9%	37.8%	39.4%	29.9	30.3%	
10%	55.6%	80.6%	83.1%	71.8%	72.8%	54.4%	55.5%	45.1	45.9%	
20%	72.0%	90.6%	92.2%	84.3%	85.0%	71.5%	72.9%	63.5	64.1%	
30%	81.7%	94.5%	95.7%	90.0%	90.7%	81.4%	82.7%	75.3	76.0%	
Tindall										
1%	15.4%	18.9%	35.9%	21.0%	28.3%	20.8%	22.8%	9.6	10.0%	
2%	27.3%	40.8%	50.9%	38.8%	43.2%	31.3%	34.5%	17.2	17.9%	
5%	47.7%	66.3%	73.8%	63.6%	66.4%	52.1%	54.5%	34.0	34.9%	
10%	65.5%	84.5%	87.4%	80.2%	81.9%	68.1%	70.9%	51.8	52.3%	
20%	80.7%	93.2%	95.8%	90.8%	92.0%	84.1%	85.9%	70.3	70.8%	
30%	87.7%	96.2%	98.2%	94.9%	95.8%	90.8%	92.0%	80.1	80.6%	
Melmore										
1%	16.2%	35.2%	51.4%	29.5%	36.0%	15.7%	19.9%	8.6	9.4%	
2%	26.3%	52.8%	62.8%	44.1%	46.9%	27.3%	30.6%	14.6	15.9%	
5%	44.4%	66.4%	78.5%	61.0%	65.1%	45.9%	49.9%	29.7	30.4%	
10%	61.3%	81.2%	88.9%	77.2%	79.8%	62.9%	66.4%	46.6	47.1%	
20%	77.9%	92.3%	96.1%	89.6%	91.1%	79.7%	81.9%	65.9	66.3%	
30%	85.6%	96.8%	98.4%	94.3%	95.2%	86.8%	88.5%	76.5	76.8%	

*TDS (total dissolved solids) flux is based on conductivity measurements.

As the percent exceedency increases, the differences in percentage of total transport associated with flow and flux exceedencies decrease. At 30% exceedencies, the percentage of the total fluxes for both flow and flux exceedency are about the same.

The three stations summarized in Table 48 have greatly differing drainage areas. The Maumee, Fremont and Melmore station have watersheds of 16,395, 3,240 and 386 sq km respectively. As the size of the drainage area decreases the flux and flow exceedency patterns appear to change in a systematic way. With respect to sediment transport, flows exceeded 1% of the time accounted for 13.6% of the total transport at the Maumee station, 18.9% at Fremont and 35.2% at Melmore. Suspended solids fluxes exceeded 1% of the time accounted for 30.8% of the sediment transport at the Maumee station, 35.9% at Fremont and 51.4% at Melmore. Parallel patterns were present for total phosphorus transport. The transport of total dissolved solids did not show this characteristic. These data do emphasize that as watersheds become smaller, greater proportion of the transport of sediment and sediment related pollutants occur in small percentages of time.

It should be noted that the time exceedency data presented above do not represent contiguous time intervals. Rather the data reflect the cumulative role of peak flows or peak fluxes taken from a number of large runoff events. The data nevertheless underscore the role of peak transport events in total material transport. In all three stations the highest 10% of the time with respect to either flows or fluxes accounted for more than 80% of the total sediment transport, more than 70% of the total phosphorus transport and more than 54% of the soluble reactive phosphorus transport.

SECTION 8

WATER QUALITY MANAGEMENT IMPLICATIONS

The river transport data described in the preceeding sections are useful in addressing a number of problems in the area of water quality management planning. These problems or questions concern: 1) the assessment of the relative costs and environmental effectiveness of point and nonpoint phosphorus control programs; and 2) the identification of critical areas for nonpoint control programs.

POINT AND NONPOINT SOURCE COMPONENTS OF STREAM PHOSPHORUS TRANSPORT

The mean annual nutrient loads calculated for the transport stations and summarized in Table 41 include the effects of both point source and nonpoint source inputs. A standard procedure for calculating the nonpoint source components of the transport is to subtract upstream point source inputs from the total stream transport (Baker and Kramer, 1973; Sonzogni; et al., 1978; COE, 1975a). Usually it is assumed that all of the point source inputs are transported through the stream system, although large portions of these inputs may be stored in temporary sinks on the stream bottom. By assuming 100% transmission of point source inputs and subtracting this value from the total stream transport, the resulting value for nonpoint components represents a minimum value. If the transmission of point source inputs is less than 100%, then smaller point source components would be subtracted from the total load and consequently the nonpoint components would be larger.

Point source loading estimates for the study watersheds were taken from sewage treatment plant records where these were available and estimated in other cases. Plants with flows both greater than and less than 3770 m³/day (1 million gallons per day) were included in the point source summaries. Phosphorus removal requirements apply primarily to plants with flows greater than 3770 m³/day. Point source phosphorus loadings have been summarized in a number of recent publications (COE, 1975b; DePinto, et al., 1979; IJC, 1979; IJC, 1980). Point sources of phosphorus in the Sandusky Basin are listed in Table 49.

Calculations of nonpoint phosphorus loading for the study watersheds are shown in Table 50. Table 50 also includes data which suggests that point source inputs do not have 100% transmission through the stream system. When the calculated nonpoint yields are divided by the total watershed area to obtain unit area nonpoint yields, the watersheds with the highest percentage of point source (Bucyrus, Portage and Huron) have the lowest unit area nonpoint phosphorus yields. These same watersheds, however, have unit area sediment yields comparable to adjacent watersheds lacking point source inputs. Consequently the nonpoint phosphorus to sediment ratios are much lower for the watersheds with higher percentages of point sources than for adjacent watersheds with similar unit area sediment loads and lacking point source inputs. There is no reason to expect nonpoint phosphorus to sediment ratios to be lower in watersheds containing point sources than in adjacent watersheds lacking point sources. The discrepancies could be resolved if the transmission of the point source phosphorus inputs were less than 100%. Even if point source inputs have 100% transmission through the stream systems they would account for only 16.3% percent of the total loads observed at the river

Table 49. Indirect municipal point source phosphorus discharges in the Sandusky River Basin 1978.

Location	Flow $10^3 \text{ M}^3/\text{day}$ (MGD)	Total Phos. mg/l	Loading Rate Kg/hr.	Annual Load M Ton/yr.
Crestline	2.1 (.55)	6*	.52	4.6
Bucyrus	7.7 (1.9)	8.0	2.6	22
Upper Sandusky	6.4 (1.7)	2.5	.67	5.8
Cary	2.3 (.6)	6*	.57	5.0
Attica	.87 (.23)	6*	.22	1.9
Bloomville	1.1 (.28)	4*	.18	1.6
Tiffin	13. (3.5)	0.9	.49	4.3
Total	33 (8.8)		5.3	45

*Estimated.

Table 50. Minimum nonpoint source phosphorus yields for the study watersheds.

Watershed	Total Phosphorus Transport t/yr.	Point Source Input t/yr.	Minimum* Non-Pt. Yield t/yr.	Unit Area Non-Pt. Yield kg/ha/yr.	Suspended Solids Yield MT/ha/yr.	Non-Pt. TP/SS Ratio g/kg	Point Source % of Total Phosphorus Yield*	Watershed Population Density #/km ²
Maumee	2200	321	1879	1.14	.63	1.81	14.6%	
Portage	108	40	68	.61	.40	1.52	37.0%	
Huron	98.4	44	54.4	.57	.59	.97	44.7%	
Sandusky Basin								
Fremont	355	45	310	.96	.52	1.85	12.7%	31
Mexico	234	37	197	.98	.65	1.51	15.8%	26
Upper Sandusky	112	32	80	1.04	.63	1.65	28.5%	46
Bucyrus	42.6	27	15.6	.68	.54	1.25	63.3%	96
Nevada	31.1	---	31.1	1.43	.87	1.64	0%	16
Tymochtee	62.9	---		1.06	.54	1.96	0%	8
Melmore	42.2	3.5	39.0	1.01	.49	2.06	8.3%	18
Wolf, East	29.8	---	29.8	1.40	.61	2.29	0%	29
Wolf, West	17.6	---	17.6	1.03	.48	2.13	0%	29

mouth stations (Maumee, Portage, Huron and Sandusky at Fremont.)

Septic tank systems are another potential source of phosphorus in the stream system. Within the Sandusky Basin upstream from Fremont the total population is about 99,600 (preliminary 1980 census data). Approximately 50% of the population is served by centralized sewage collection systems and treatment plants while the other 50% is served by septic tanks. Although some septic tank effluents containing phosphorus enter the stream systems, studies conducted below the town of Tyro in the Honey Creek watershed indicated that stream loading associated with septic tank inputs was quite small (Krieger, et al., 1980).

The dominance of agricultural land use within the study watersheds suggests that the bulk of this nonpoint phosphorus loading is derived from rural, rather than urban land uses. The unit area nonpoint phosphorus loading rates are actually higher in watersheds which lack urban areas (Nevada, Tymochtee, Melmore, Wolf East and Wolf West) than for watersheds containing urban areas. For the Lake Erie Basin as a whole the PLUARG studies indicated that 61% of the tributary phosphorus loads were derived from cropland, 5% from pasture, 21% from urban and 13% from other land uses (PLUARG, 1978). The ratios of urban land to cropland would be much lower in the study watersheds than the average ratio for Lake Erie.

STREAM PROCESSING OF POINT SOURCE PHOSPHORUS INPUTS

The phosphorus concentration profiles presented in Figures 18 and 19 illustrate that phosphorus entering stream systems rapidly disappears from the flowing water. Biological uptake by the periphytic and benthic communities, adsorption onto sediments and chemical precipitation could all be involved in the removal of total phosphorus from the flowing water. This processing of phosphorus by the stream system has been noted by numerous authors (Keup, 1968; Thomann, 1972; Verhoff, et al., 1978; Verhoff and Baker, 1980).

The extent of phosphorus deposition below point sources in the Sandusky Basin has been analyzed using both concentration data and flux data (Baker, 1980). The combined point source loading rate in the Sandusky Basin upstream from Fremont is about 5.3 kg/hr (see Table 49). The phosphorus flux exceedency tables at Fremont (see summary in Table 48) indicate that 55% of the time the flux is less than 5.3 kg/hr and the cumulative flux during that 55% of the time accounted for only 2.14% of the total phosphorus flux observed at the Fremont station.

The computer printouts for flux exceedency include both the cumulative hours and the cumulative flux (see Table 21). In this case, 55% of the time amounted to 16,806.4 hours and during this time the stream transported 30,043.7 kg of P. Thus the average phosphorus flux during the 55% of the time with the lowest flux was 1.79 kg/hr. This flux includes both phosphorus from point sources and "background" phosphorus following the hydrological pathways of water under these flow conditions.

At Fremont, 55% of the time the flows were less than 326 CFS and flows during this 55% of the time accounted for 2.41% of the total observed phosphorus flux. Thus at these exceedency levels, flux and flow rankings are very similar in terms of their accompanying percent of total transport. The average flow during the 55% of the time with the lowest flows was 145 CFS. Since the combined flow from all the sewage treatment plants is only about 14 CFS it is clear that the bulk of the flow (131 CFS) during this portion of the time is derived from hydrological pathways such as ground water, tile effluent and surface water rather than point sources.

In the watersheds lacking point sources, the total phosphorus concentrations averaged about 0.12 mg/l during the 55% of the time with the lowest flows. Assuming that this concentration characterized the nonpoint or "background" concentration of the stream flow, the average nonpoint loading

rate would be about 1.6 kg/hr ($131 \text{ CFS} \times 0.12 \text{ mg/l} \times 0.10188$). Since at Fremont, the average total loading during this time period is 1.8 kg/hr, it is clear that most of this phosphorus can be attributed to nonpoint rather than point source inputs. With point source phosphorus input rates of 5.3 kg/hr, and with only about 0.2 kg/hr of the average output for 55% of the time allocable to point sources, it is also clear that these streams are capable of removing most of the point source phosphorus inputs from the flowing water.

The 55% time period in the above calculations was selected because in the flux exceedency tables 55% of the time the fluxes at Fremont were below the point source input rate of 5.3 kg/hr. Since much of that phosphorus loading would be due to nonpoint sources, deposition of point source phosphorus must also be occurring at higher flows and fluxes.

Municipal point sources which load phosphorus into tributaries upstream from gaging stations nearest Lake Erie are considered indirect point sources with respect phosphorus loading (IJC, 1979). Direct point sources are those whose outfalls enter streams below the gaging station nearest the lake, or enter estuaries or the nearshore zone of the lake. The effectiveness of phosphorus control programs at indirect point sources in reducing eutrophication in Lake Erie depends on the extent of resuspension and eventual delivery of this phosphorus to the lake and on its bioavailability upon reaching the lake. The significance of information on transmission and bioavailability in phosphorus management is illustrated in the Watershed Model (Sonzogni, et al., 1980; Montieith, et al., 1980).

Analysis of hydrograph patterns at Sandusky gaging stations coupled with wave and water routing techniques indicate that sediment resuspension is an important component of sediment transport in this basin (see Section 9). It is usually assumed that phosphorus derived from point sources becomes part of the particulate phosphorus which is resuspended and moved downstream by the passage of wave fronts associated with storm flows (Verhoff, et al., 1978). The question of the transmission of point source phosphorus to the lake becomes a question of the instream transmission or delivery ratio of particulates to the lake. Reservoir sedimentation or flood plain deposition could transfer point-source-derived phosphorus into long term sinks and consequently reduce the transmission of this phosphorus below 100%. It is also possible that phosphorus could be removed from stream systems through food chains or other biological means.

As noted earlier indirect evidence associated with the calculation of nonpoint phosphorus loads and phosphorus-sediment ratios suggest that the transmissions of point source phosphorus through stream systems is less than 100%. Precise and direct measurements of point source phosphorus transmission factors will, however, be very difficult to obtain because of the large annual variations in phosphorus transport and phosphorus/sediment ratios. It is also probable that the "transit time" of phosphorus movement through the stream will be variable. The best opportunities for measuring transmission factors would be in locations where point source phosphorus comprises a large portion of the phosphorus output and where long term yield measurements are conducted both prior to and following a substantial reduction in point source inputs. In the Sandusky Basin the best opportunity for such studies would be at the Upper Sandusky gaging station following implementation of a phosphorus removal program at Bucyrus, Ohio.

With respect to bioavailability, it is probable that the point-source-derived phosphorus that does reach the lake is largely incorporated into the particulate fraction. Within the phosphorus transport model developed by the U.S. Army Corps of Engineers in the LEWMS study, there is no evidence of a release of soluble phosphorus from sediments during the passage of storm events (Yaksich & Adams, 1980). Since point-source-derived phosphorus is largely bioavailable upon entry into a stream, it is also considered largely bioavailable upon subsequent delivery to receiving waters (Monteith, et al., 1980). Data from the Sandusky does not support this conclusion.

Considerable attention is now being directed to the bioavailability of particulate phosphorus (Sonzogni et al., 1981; Logan 1978b; Armstrong, et al., 1979; Lee et al., 1980). These studies suggest that NaOH-extractible phosphorus provides a good measure of bioavailable particulate phosphorus. In Table 51, data from Logan (1978b) on the NaOH-extractible -P from the study watersheds is presented. The NaOH-extractible fraction comprises, on the average, 36.4% of the persulfate-digestible particulate -phosphorus. Persulfate rather than perchloric acid digestible particulate phosphorus was selected from Logan's data, since the total phosphorus procedure used in our lab involves persulfate digestion. The data in Table 51 indicate that there is considerable variability in the proportion of bioavailable particulate phosphorus at a given station. The average value of 36.4% does, however, agree very closely with the 35% bioavailable portion reported for the Maumee River by Armstrong, et al., (1979).

The average percent availability is slightly higher for strictly agricultural watersheds such as Wolf, West and Broken Sword than it is for the other stations which include much larger point source inputs in their watersheds (see Table 50). This would not be expected if point-source-derived phosphorus became largely incorporated into the bioavailable particulate fraction. At the Fremont station, the mean annual particulate phosphorus loading is 278.5 metric tons per year. Assuming 35% of this is bioavailable, the bioavailable particulate phosphorus loading would be 97.5 metric tons per year. If all of the point source phosphorus inputs upstream from Fremont (45 metric tons per year) were exported as bioavailable particulate phosphorus, the point source inputs would make up 46% of the total export of bioavailable phosphorus from the basin. It would then be expected that the percent bioavailability would be much greater along the mainstream of the river below point sources than from watersheds lacking or with very small point source inputs. Data presented in Table 51 do not support this. Instead the data suggest that, upon delivery to the lake, either the bioavailability of point-source -derived phosphorus is no greater than the bioavailability of nonpoint source particulate phosphorus or that the transmission of point-source-derived phosphorus is much less than 100%.

It should also be noted that most of the soluble reactive phosphorus delivered to the lake from tributaries is derived from nonpoint sources. The flux exceedency tables for the Fremont gage indicate that 70% of the soluble phosphorus flux is delivered in 10% of the time. On an annual basis this corresponds to 53.5 metric tons of soluble reactive phosphorus during 10% of the year. Since point source inputs are relative constant year round, they could account for only 4.5 metric tons during the time when the total export was 53.5 metric tons. Even if soluble phosphorus from point sources moved

Table 51. Analyses of NaOH-Extractable P from suspended solids collected during runoff events of study watersheds. (after Logan, 1978b).

Station	Date	Suspended Solids mg/l	Persulfate-Total Phosphorus ug/g	NaOH-Ext. Phosphorus ug/g	Percent NaOH-Ext. Phosphorus
Waterville	3/10/77	143	1168.2	426	36.4%
	4/26/77	248	1197.9	309.9	25.8%
Portage	3/28/77	160	1267.2	442.2	34.9%
	7/5/77	318	1049.4	276.4	34.9%
Fremont	3/28/77	376	1019.7	480.8	47.1%
	7/2/77	278	1297.0	395.2	30.1%
	7/3/77	730	970.2	290.6	30.0%
Mexico	3/28/77	340	1029.6	359.5	34.9%
Upper Sand.	3/28/77	288	900.9	317.3	35.2%
Bucyrus	3/28/77	224	702.9	261.5	37.2%
Honey Creek	3/21/77	120	940.5	434.9	46.2%
	3/28/77	160	663.3	423.9	64.9%
	4/5/77	114	1194.0	388.3	32.5%
	7/1/77	1184	861.3	354.1	41.1%
Broken Sword	7/1/77	1204	910.8	332.3	36.4%
	7/2/77	194	861.3	259.2	30.1%
Wolf, West	7/1/77	370	1148.4	311.5	27.1%
Wolf, East	3/28/77	198	871.2	283.6	32.5%
Huron	7/5/77	1008	792	267.8	33.8%

directly through the stream system without processing, during periods of high stream flow, it could account for only a small portion of the soluble phosphorus loading to the lake.

In considering both soluble reactive phosphorus and bioavailable particulate phosphorus the evidence cited above indicates that nonpoint-derived phosphorus has a higher bioavailability upon delivery to the lake than indirect point-source-derived phosphorus.

COMPARISON OF PHOSPHORUS INPUTS FROM TRIBUTARIES AND DIRECT POINT SOURCES

Since the early 1970's, phosphorus loading to the Great Lakes from point sources has been decreasing due to municipal phosphorus removal programs and detergent phosphorus controls. In the mid 1970's point source loading became smaller in magnitude than nonpoint-derived phosphorus loading (COE, 1975; PLUARG, 1978). Although there has been much progress in reducing phosphorus loading to Lake Erie through the implementation of phosphorus removal programs at municipal sewage treatment plants, still further reductions in phosphorus

loading are required to meet the target loads adopted in the 1978 Great Lakes Water Quality Agreement (IJC, 1980; IJC, 1981). Two programs are attempting to identify the most cost effective strategies for achieving the target loads (PLUARG, 1978; COE, 1979).

A primary issue in the development of these strategies concerns the relative costs and effectiveness of point source and nonpoint source controls in reducing the eutrophication of Lake Erie. Considerable data is available on the costs of varying levels of phosphorus removal at municipal wastewater treatment plants (Drynan, 1978). Much less information is available on the costs of nonpoint controls. In the Lake Erie basins these controls are aimed primarily at reducing cropland erosion. Both the PLUARG and LEWMS studies have included demonstration projects in which estimates of the costs of implementing nonpoint controls can be based. A variety of conservation tillage programs appear to be very economical to farmers in this region (COE, 1979; Forster, 1978). It is significant that the soils most suitable for no-till crop production are also the soils with the highest gross erosion rates (Table 7). However, there is no correlation between gross erosion rates and nonpoint phosphorus loading rates (Figure 23). Unfortunately the effectiveness of erosion control in reducing phosphorus export from large river basins has yet to be demonstrated through large scale implementation and long term monitoring programs. Currently estimates of phosphorus load reductions are largely based on assumptions about sediment delivery ratios and enrichment ratios. Consequently information on the costs per unit of phosphorus load reduction is much less certain for nonpoint source controls than for point source controls.

The relative effectiveness of point and nonpoint phosphorus controls in reducing the eutrophication of Lake Erie is also subject to question. As noted above, upon entering the stream or lake system, point-source-derived phosphorus is largely bioavailable while nonpoint-derived phosphorus is only about 50% available. The bioavailable phosphorus from nonpoint sources is composed of approximately equal portions of soluble and bioavailable particulate phosphorus. It has already been suggested by numerous authors that consideration of bioavailable phosphorus should be incorporated into future analyses of cost effectiveness (see review by Sonzogni, et al., 1981). These considerations tend to increase the cost effectiveness of point source controls relative to nonpoint controls.

Research in northwestern Ohio rivers suggests that temporal, spatial and hydrodynamic aspects of phosphorus loading could also be very important in comparing the effects of point and nonpoint inputs. In stream systems, point source inputs are processed very rapidly, resulting in deposition and probable reduction in subsequent bioavailability. Direct point source phosphorus inputs into the lower section of rivers, estuaries, bays, and even the near shore zone of the lake, may also be subject to rapid processing, resulting in deposition and/or conversion to less bioavailable forms. The susceptibility of point source inputs to efficient processing may be associated with the constant rather than pulsed nature of these inputs. The annual point source inputs are delivered to aquatic systems at approximately constant daily rates. The processing of this phosphorus may be associated with significant localized water quality problems.

In contrast the nonpoint-derived phosphorus is delivered in association with runoff events. Large portions of the annual loads are delivered in a small percentage of the time. During periods of nonpoint loading the retention time of water in the lower sections of rivers, estuaries, bays and even the nearshore zone of the lake would be much shorter. Consequently soluble nonpoint-derived phosphorus may be much less susceptible to processing within these zones than point-source-derived phosphorus. Since much of the particulate phosphorus of nonpoint origin is associated with clay-sized particles, this material may also be delivered rather efficiently through the estuaries, bays and the nearshore zone to the open lake.

It should also be noted that the concentrations of both soluble and total phosphorus in rivers during periods of high flows are much higher than the phosphorus concentrations in lake water. Also, point source phosphorus from the Detroit area enters the western basin of Lake Erie at much lower concentrations than nonpoint-derived phosphorus, due to the large volume of water with low phosphorus concentration entering the Detroit River from the Upper Lakes.

The above discussion suggests that temporal, spatial and hydrodynamic aspects of phosphorus loading and accompanying processing need to be included, along with bioavailability, in refining cost-effectiveness analyses for phosphorus management of Lake Erie.

SEDIMENT DELIVERY RATIOS AND CRITICAL AREA IDENTIFICATION

The data on mean annual sediment yields (Table 41) coupled with the data on gross erosion rates (Table 7) allow calculation of sediment delivery ratios for each watershed. These are summarized in Table 52. The calculated sediment delivery ratios ranged from 6.2 to 11.9%.

There have been very few measurements of sediment delivery ratios for watersheds in this size range. In Figure 22, the delivery ratios measured in these watersheds are superimposed on a plot of delivery ratios in relation to drainage area. The original data is presented in Soil Conservation Service publications (SCS, 1971) and is often used in modeling studies (McElroy et al., 1976). Although the study watersheds do occur in roughly the appropriate position in the plot, they do not follow the trend of decreasing delivery with increasing drainage area exhibited by the other watersheds.

Linear regressions between sediment delivery ratios and other watershed parameters listed in Table 52 are shown in Table 53. Of these, the only significant correlation was an inverse correlation between gross erosion rate and sediment delivery ratio. In addition, there was no significant correlation between gross erosion and sediment yield or gross erosion and nonpoint phosphorus yields for these watersheds. Figure 23 illustrates a plot of gross erosion and nonpoint phosphorus losses.

The above data indicate that neither sediment yields nor nonpoint phosphorus yields are predicted very well by average gross erosion rates in watersheds of the sizes included in this study. The lack of correlation between gross erosion and yields of sediment and phosphorus raises significant questions about the effectiveness of programs which propose to reduce sediment

Table 52. Sediment delivery ratios for Northwestern Ohio agricultural river basins

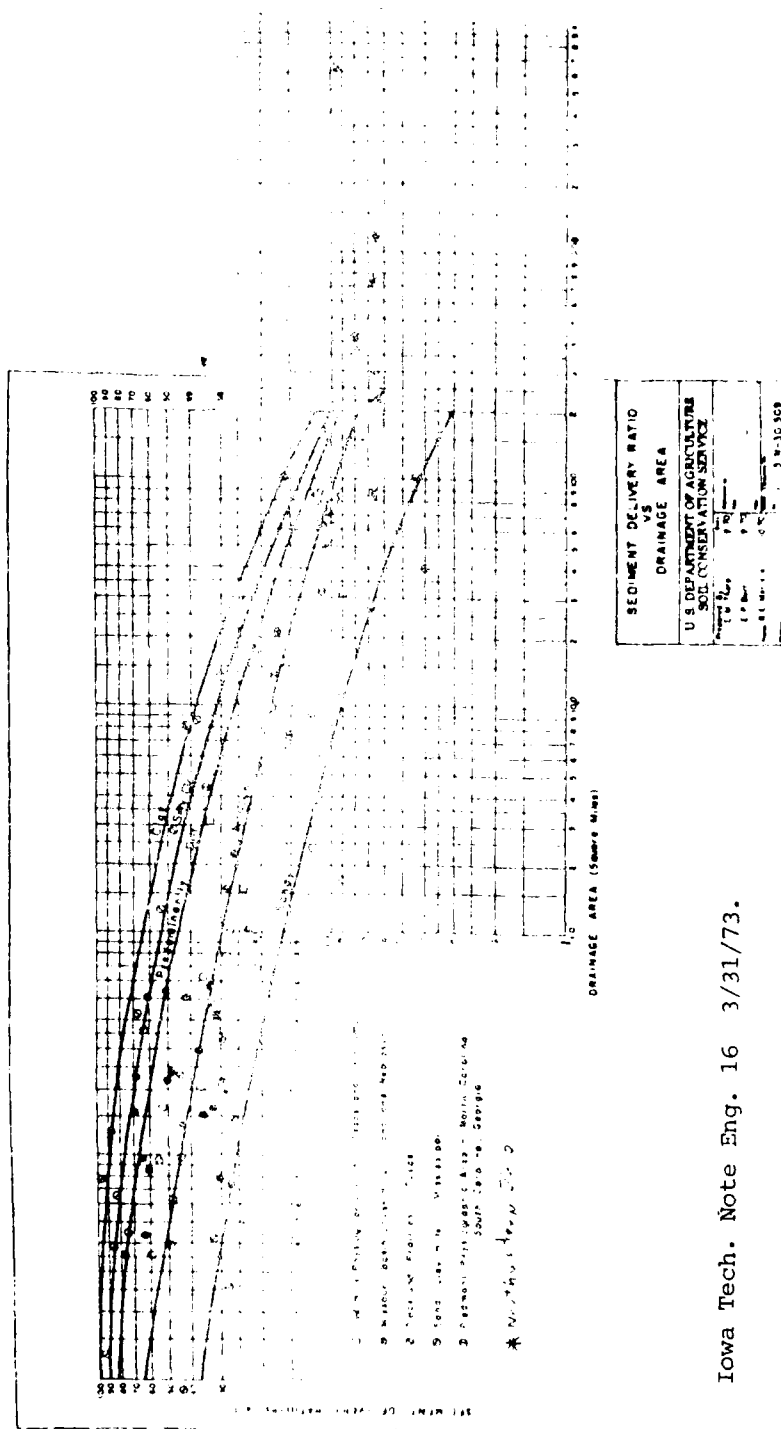
Gaging Station	Watershed Area Km ²	Mean Annual Flow cm/yr.	Gross Erosion Tons/ha/yr.	Sediment Yield Tons/ha/hr.	Delivery Ratio %
Maumee	16,395	26.3	6.84	.63	9.2%
Portage	1,109	25.1	5.00	.40	8.0%
Huron	961	27.9	7.51	.59	7.9%
Sandusky	3,240	26.3	8.25	.52	6.3%
Mexico	2,005	25.7	9.37	.65	6.9%
Upper Sandusky	772	28.0	9.35	.63	6.8%
Bucyrus	230	32.9	7.85	.54	6.9%
Tymochtee	593	25.8	8.41	.52	6.2%
Honey	386	27.1	6.86	.49	7.1%
Nevada	217	35.6	9.39	.87	9.2%
Wolf, East	213	33.5	5.11	.61	11.9%
Wolf, West	171.5	26.0	4.19	.48	11.5%

Table 53. Linear regressions relating to delivery ratios, sediment yields, and nonpoint phosphorus yields.

X	Parameters	Y	Slope	Intercept	r ²	DF
Watershed Area		delivery ratio	0.0000	8.09	0.5%	10
Watershed Area ^{0.2}		delivery ratio	-0.3639	9.58	5.15%	10
Runoff cm		delivery ratio	0.184	2.95	11.6%	10
Gross Erosion rate		delivery ratio	-0.737	13.6	47.1%**	10
Gross Erosion rate		sediment yield	0.0298	0.3517	22.5%	10
Gross Erosion rate		unit area nonpt. phos.**	-0.0126	1.222	2.0%	7

*significant at the p = 0.05 level.

**excludes Bucyrus, Huron and Portage basins.



Iowa Tech. Note Eng. 16 3/31/73.

Figure 22. Relationship between sediment delivery ratio and drainage area.

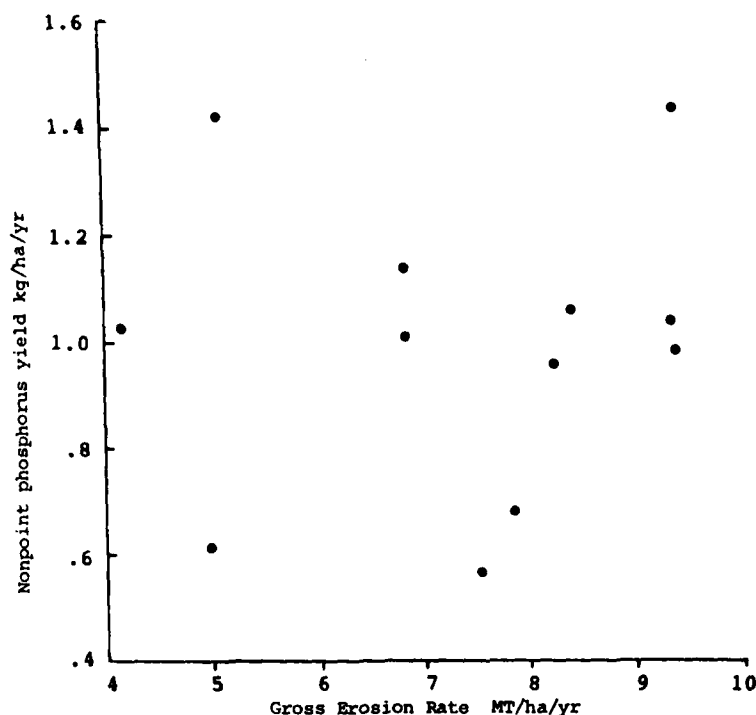


Figure 23. Relationship between nonpoint phosphorus export and gross erosion rates in the study watersheds.

and phosphorus yields by reducing gross erosion in the watersheds. It should be noted that the differences in gross erosion between the various watersheds listed in Tables 7 and 52 reflect erosional difference under conventional tillage where ground cover is very low. The rather uniform sediment and phosphorus yields from these watersheds may reflect approximately equal unit area clay export from these soils. Those areas with higher gross erosion rates may simply have lower delivery ratios due to deposition of larger particles. Conservation tillage practices which increase ground cover could reduce the entrainment of clay particles, thereby reducing sediment and particulate phosphorus losses as well as gross erosion. This effect could be independent of gross erosion rates. Thus with respect to reducing sediment and particulate phosphorus yields to Lake Erie, "critical areas" may not exist and, instead, efforts should concentrate on implementing various conservation tillage practices wherever the combination of suitable soils and technology are present. There may be more opportunities for implementing such programs in areas with lower gross erosion rates than in areas with higher gross erosion rates. The benefits to the lake could be proportional to the areal extent of conservation tillage implementation rather than to the reduction in gross erosion per se. It is quite possible that the proportional reduction in sediment and phosphorus yields could be greater than the reduction in gross erosion for a large watershed.

The interpretation presented above differs in some significant ways from interpretations upon which many current nonpoint control planning programs are based. Most current programs involve critical area identification through using some combination of information on gross erosion rates, sediment delivery ratios, or hydrologically active areas. Projected decreases in phosphorus loading are presumed to be proportional to reductions in gross erosion, multiplied by a factor less than one (1) which takes into account shifts in particle sizes and accompanying phosphorus export. In small watersheds the proportional reduction in phosphorus export is less than the reduction in gross erosion. In large watersheds the same does not necessarily hold since delivery ratios may differ in various parts of the watershed and these ratios may be inversely correlated with gross erosion rates.

SECTION 9

TRANSPORT MODELING

The network of transport stations in the Sandusky Basin has been used for the study of material transport along the mainstream of river systems. Of particular interest has been the development of an explanation for the advanced sediment and phosphorus concentration peaks relative to the hydrograph peaks that persist from station to station as storms move down the mainstream of the river. Since the storm wave moves downstream faster than the water flows downstream, the water containing peak sediment and phosphorus concentrations during the early stages of a hydrograph at an upstream station cannot be the same water that contains the peak concentrations of sediment and phosphorus during the early phase of a hydrograph at a downstream station.

Two explanations for the persistence of advanced peaks have been proposed. One involves routing of materials from various areas in the watershed to the stream gages. The second involves the incorporation of deposition/resuspension phenomena applicable to all components of the suspended sediment transport, including the clays.

A model was developed for material transport in the river which included both the wave and water velocities. Only when deposition and resuspension of sediments and phosphorus was incorporated into the model, could the patterns of sediment and phosphorus concentrations at downstream stations be duplicated. The routing models also allow calculations of deposition and resuspension of materials as shown in Figure 24.

These models have been developed as part of the Lake Erie Wastewater Management Study and are described in detail in the Technical Report Series associated with that study (Verhoff et al., 1978; Melfi & Verhoff, 1979; Yaksich & Adams, 1980; COE, 1979).

As part of this study, a generalized river transport model based on the above work was developed at the University of West Virginia under subcontract from Heidelberg College. A paper presenting the generalized model is included in the appendix of this report.

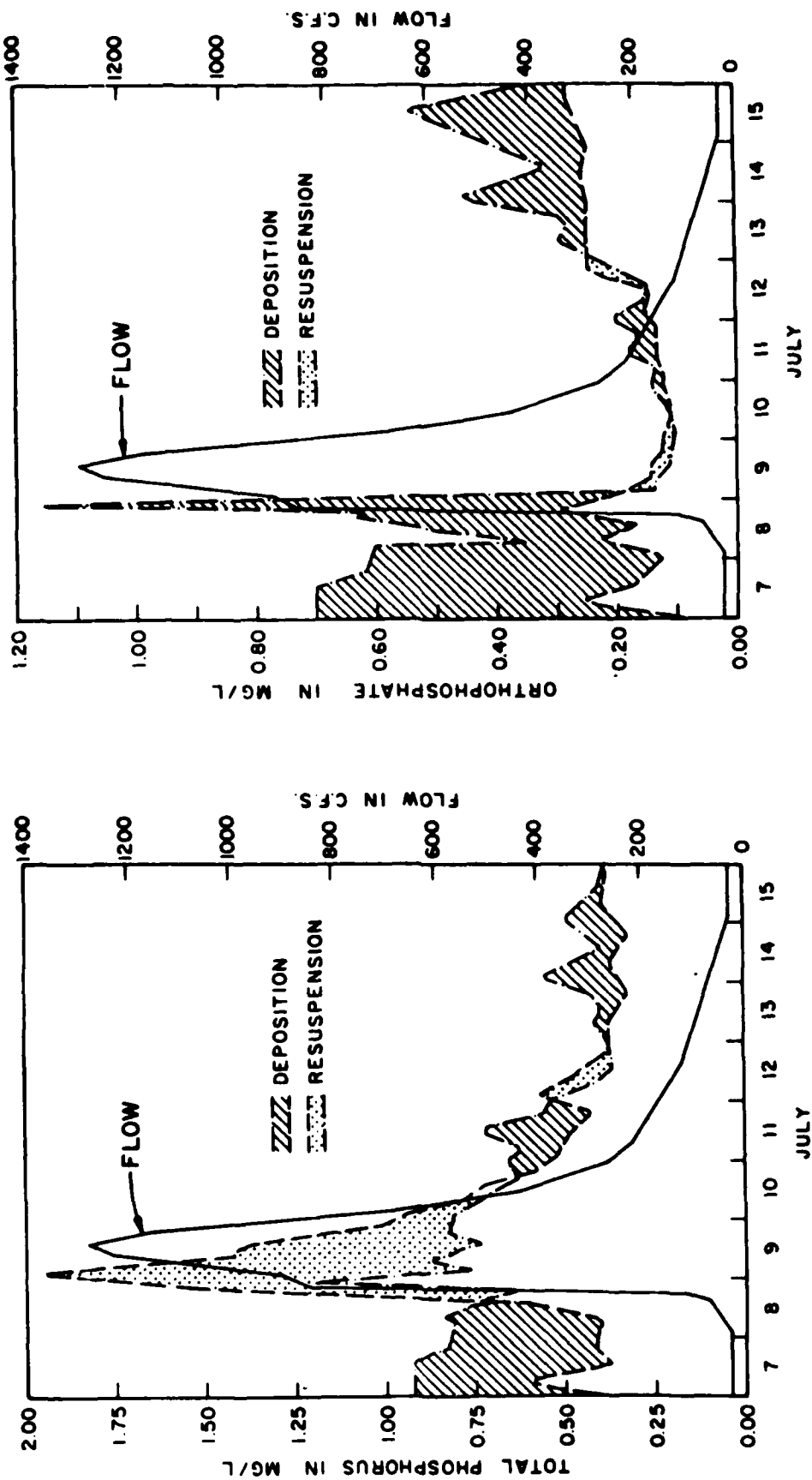


Figure 24- Deposition and Resuspension of (a) Total Phosphorus and (b) Orthophosphate in the Sandusky River near Upper Sandusky - Storm beginning 7 July 1976. Source: Melfi & Verhoff, 1979.

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APPENDIX 1

ANALYTICAL METHODS

Soluble Reactive Phosphorus (Modified colorimetric ascorbic)
Storet No. 00671

Scope and Application - Methods for phosphorus are based on reactions specific for the orthophosphate ion. The methods cover the determination of specific forms of phosphorus present in surface waters. The sample pretreatment determines the form of phosphorus to be measured.

For dissolved orthophosphorus the sample is filtered through a prewashed follows using a modified Method 365.1 from Methods for Analysis of Water and Wastes. U.S. Environmental Protection Agency, National Environmental Research Center, Cincinnati, Ohio, 1979. EPA-600/4-79-020, pages 365.1-1 - 365.1-9.

The method has been modified from the single reagent method in several ways. First, the ascorbic acid is a separate reagent and is added to the analytical stream in place of the distilled water, and in effect we make our mixed reagent within the analytical system. By doing this our mixed reagent has a shelf life of several months, not the four hours as in the EPA method. We also put a much larger volume (sample & reagent) through our analytical system. This results in a more reliable system and improves flow cell clean out.

Nitrate and Nitrite Nitrogen (automated cadmium reduction)
Storet No. 00631

Prior to analysis by cadmium reduction from Method 353.2 from Chemical Analysis of Water and Wastes, U.S. Environmental Protection Agency, National Environmental Research Center, Cincinnati, Ohio, 1979. EPA-600/4-79-020, pages 353.2,2-7. The samples are filtered through a .45 micron pore size membrane filter.

Ammonia (colorimetric automated phenate) Storet No. 00608

The sample is filtered through a .45 micron pore size membrane filter and analyzed using Method 350.1 from Chemical Analysis of Water and Wastes, U.S. Environmental Protection Agency, National Environmental Research Center, Cincinnati, Ohio, 1979. EPA-600/4-79-020, pages 350.1-1 - 350.1-6.

Chloride (colorimetric automated Ferricyanate) Storet No. 00940

Following filtration through a membrane filter with a pore size of from the Chemical Analysis of Water and Wastes, U.S. Environmental Protection Agency, National Environmental Research Center, Cincinnati, Ohio, 1979. EPA-600/4-79-020, pages 325.2-1 - 325.2-3.

Sulfate (colorimetric, automated, methylthynol Blue) Storet No. 00945

The samples are filtered through a .45 micron pore size membrane filter prior to analysis by Method 375.2 from Chemical Analysis of Water and Wastes, U.S. Environmental Protection Agency, National Environmental Research Center,

Cincinnati. Ohio. 1979. EPA-600/4-79-020. pages 375.2-1 - 375.2-3.

Silica (colorimetric molybdate reactive) Storet No. 00955

Samples are filtered through a .45 micron membrane filter prior to analysis using Technicon Industrial Method 105-71W from Technicon Industrial Systems, Tarrytown, New York, 10591, February 1973.

Total Phosphorus Storet No. 00665

A 50ml aliquot of a well mixed sample is placed in a 125ml Erlenmeyer flask. One milliliter (automatic pipette) of strong acid and four-tenths of a gram (pre measured scoop) of ammonium persulfate are then added to the flask. Two blanks and four standards are prepared with each batch of samples. After autoclaving (45 minutes) at 15 lbs. pressure and 121 degrees C. the samples are filtered through a glass fiber filter (pre filter pore size) to remove turbidity and poured out into tubes for analysis on the total phosphorus autoanalyzer. This method is a modification of Method 365.1 (see SRP) from the Chemical Analysis of Water and Wastes, U.S. Environmental Protection Agency, National Environmental Research Center, Cincinnati, Ohio, 1979. EPA-600/4-79-020, pages 365.1-1 - 365.1-9.

When the samples are removed from the autoclave, those samples which had high amounts of suspended matter are checked to confirm that the residue is white to light grey in color. If color is present the sample(s) are set up again and digested with larger amounts of persulfate.

Total Kjeldahl Nitrogen (colorimetric, automated phenate) Storet No. 00625

A 10ml* aliquot of a well mixed sample is placed in a 75ml digestion tube. Four milliliters (by repipet) and 2-3 Teflon boiling chips are added to each tube, and the sample-acid solution is vortexed before the sample set is put on the block. The block is set for 2 temperatures and 2 times. The first temperature is 180 degrees C for 1 hour, the second temperature is 380 degrees C for 3 hours. When the digestion is completed, the tubes are taken off the block and allowed to cool down. Ten milliliters of distilled water is added to each tube to get back to the original volume. Before pouring the sample out into test tubes, the samples are vortexed again to get a thorough mixture of distilled and digested acid. At this point any residue from suspended solids should be light grey or off white in color, if color is present, consult with the lab manager. Analysis follows using Method 351.1 from Chemical Analysis of Water and Chemical Analysis of Water and Wastes, U.S. Environmental Protection Agency, National Environmental Research Center, Cincinnati, Ohio, 1979. EPA-600/4-79-020, pages 351.1 - 351.1-4.

*Volume varies with sample type.

Conductivity

Specific conductance is measured using a Water Quality Laboratory conductivity meter (product of WQL) and a Yellow Springs Instrument (YSI) conductivity cell. Samples are run at 25 degrees. This is in accordance with Method 120.1 from Methods for Analysis of Water and Wastes, U.S. Environmental Protection Agency, National Environmental Research Center, Cincinnati, Ohio, 1979. EPA-600/4-79-020, page 120.1.1.

pH (potentiometric) Storet No. 00400

pH measurements are determined using a glass combination electrode with an Orion 701 digital pH meter. The samples are run at 25 degrees C following the guidelines for Method 150.1 in Methods for Analysis of Water and Wastes, U.S. Environmental Protection Agency, National Environmental Research Center, Cincinnati, Ohio, 1979. EPA-600/4-79-020, page 150.1-1.

Specific Conductance

Specific conductance is measured using a Water Quality Laboratory conductivity meter (product of WQL) and a Yellow Springs Instrument (YSI) conductivity cell. Samples are run at 25 degrees. This is in accordance with Method 120.1 from Methods for Analysis of Water and Wastes, U.S. Environmental Protection Agency, National Environmental Research Center, Cincinnati, Ohio, 1979. EPA-600/4-79-020, page 120.1.1.

Suspended Solids (Residue, Non-Filterable)

A 100 ml aliquot of a well mixed sample is vacuum filtered through a pre-weighed glass fiber filter. The residue retained on the filter is dried to a constant weight at 103 degrees - 105 degrees as described in Method 160.2 in Methods for Chemical Analysis of Water and Wastes, U.S. Environmental Protection Agency, National Environmental Research Center, Cincinnati, Ohio, 1979. EPA-600/4-79-020, pages 160.2-1 - 160.2-3.

APPENDIX 2

Integral Methods for Approximate Water
and Pollutant Transport in Rivers

W. C. Peterson

Department of Mathematics

and

F. H. Verhoff

Department of Chemical Engineering

West Virginia University

Morgantown, WV 26506

ABSTRACT

Integral Methods for Approximate Water
and Pollutant Transport in Rivers

W.C. Peterson, Department of Mathematics

and

F.H. Verhoff, Department of Chemical Engineering

West Virginia University

Morgantown, WV 26506

Mass balances in an integral form are used for both water and transported material in solution.

The integral form for the water leads to a general approximation for water routing of which the Muskingum method is a special case.

The integral form of the mass balance for the transport of material leads to a general approximation for material transport which can be coupled with the method above for water routing to obtain both flow rate and concentration at a downstream location from known upstream data based primarily on knowledge of the flow vs area curve at upstream and downstream locations. Parameters in the approximation are obtained from knowledge of the channel and material in solution. The parameters are obtained to be functions of the wave and/or water velocity.

The approximation was applied to data from the Sandusky River in Ohio.

INTRODUCTION

The input of substances from point and non-point sources causes concentration changes within the river itself and within the receiving water body. The basic concept used to mathematically model these chemical changes is the mass balance. This balance can be applied to both the water itself and/or to the chemical species of interest. Also, it can be used for the prediction of in-river water quality or it can be used to predict the amount of substance transported through the river. Streeter and Phelps [1925] probably were the first to use the mass balance on a chemical substance, in this instance BOD. They were interested in steady flow and hence the water mass balance took the simple form of constant water velocity. Their mass balance on BOD then predicted the BOD and oxygen concentrations as a function of distance in the river, i.e. in river quality.

This paper focuses on the transport of substances through river systems particularly during storms rather than on the in-river water quality. The transport of substances during storms is important because much of the water and associated chemicals reach the receiving water body, e.g., lake, during storms. For example, total phosphorus, a principal nutrient in lake eutrophication, is primarily transported during storms. Chloride also is transported during winter storms from roadways of northern areas.

The modeling of chemical transport during storms requires a mass balance for both the water and the chemical substance of interest. The

solution of the water mass balance during storms has been investigated for many years and is often called water routing. The main goal of this prior research has been prediction of the flood peak as it moves downstream. Much less work has been done on the solution of both the transient water mass balance and the transient chemical mass balance as is applicable during storm transport.

Herein, an integral method for solving the water and substance mass balances between two different stations on the river is developed. This is in contrast to the finite difference approximate solutions which have been the main methods previously employed. Essentially, the mass balances are integrated between the two stations of the river, including the input from tributaries and unmeasured areas. Thus if the concentrations and flows are known at the upstream station and at the tributary mouths, and the flow and concentration of the unmeasured inflow can be estimated, the concentration of the pollutant at the downstream station on the river can be calculated. This integral method could be used to predict the concentration or aid in the understanding of the transport of various chemical species in rivers.

Much research has been done related to the transport of substances in rivers. Basically, the research work can be classified as storm vs steady flow, and correlational vs deterministic models. Various correlations have been found between the concentration of different chemical species during steady flow (see Enviro Control [1972]). Also, the relationship between various chemical concentrations and between concentration and flow has been the subject of numerous authors, e.g. Foster [1978] and Feller and Kimmins [1979]. They have found that some

substances as total phosphorus and suspended sediment concentrations increase with flow and that there is a correlation between these two concentrations. On the other hand species such as chloride usually decrease in concentration with increasing flow. The variability of the concentration is dependent upon the particular locality and upon the season of the year. These studies are not deterministic and do not provide a quantitative understanding of the processes involved in the transport, however, they do help discriminate between various plausible mechanisms for chemical transport.

Deterministic models for the transport of materials in rivers has been attempted since the original work of Streeter and Phelps [1925] which was applicable to rivers under steady flow. These river models have been made more complex to incorporate more of the nutrient and chemical cycling mechanisms (see Chen [1970] and Sandavol, et al. [1976]) who have used these models for predicting the expected concentrations of various substances as a function of stream distance and time. Further, steady flow models have been used with transient concentration variations to discriminate between models and to determine parameters within models, e.g. Verhoff and Baker [1981].

However, the number of researchers who deterministically modelled the transport of substances during unsteady flow is rather limited, except for the transport of suspended sediment. These suspended sediment models usually involve mechanisms for the resuspension and deposition of sediment particles of different sizes and they are primarily used to predict changes in stream bed morphology ie, points in the stream

where scour and deposition can occur e.g. U.S. Army Engineers HEC [1977]. Yalim [1972] has summarized various of these deterministic models used to describe this suspended sediment transport. In a recent paper, O'Conner [1976] considers the interaction of ground-water and surface water in the transport of chemical substances. He primarily was interested in steady flow but he does present examples of unsteady flow. Since unsteady hydrological models have been available for some time, there have been several attempts to couple the transient chemical dynamics to these transient water models. These storm water models are primarily finite difference solutions of the governing equations coupled with various correlations. Schultz and Wilmarth [1978] have applied the Hydrocomp Simulation Programming model to water quality in Southwestern Illinois. This model starts with the precipitation and predicts the hydrograph in the river followed by the concentration of various substances as a function of time at different points in the river. For the one storm event present in the article the predicted hydrograph did not correspond closely with the measured one. They also showed reasonable comparisons between predicted and measured concentrations under relatively stable flow conditions.

INTEGRAL REPRESENTATIONS

The technique to be described uses the assumption that water is moving as a kinematic wave. The data calculated will be derived from information given at one point on the river reach, thus the assumption that a given reach of the river is similar to the measurement point has been made. In the following discussion parameters will be determined dependent on knowledge of the wave velocity and of the water velocity at an upstream and downstream measuring station over a short river reach. The water and wave velocity at a point on the river reach can be determined from the flow vs channel cross-section area curve. This relationship, such as given in figure 1, can be represented by the equation

$$Q = f(A) \quad (1)$$

where Q is the river flow rate and A is the channel cross-section area, f may be a multi-valued function relationship depending as to whether the hydrograph at a point in the river is rising or falling with respect to time. From kinematic theory of hydrologic events the wave velocity is determined by the slope $f'(A)$ of the curve given by $Q = f(A)$ and the water velocity is given by Q/A .

For kinematic waves, the continuity equation for open channel flow has the form

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \quad (2)$$

in which t = time, x = distance measured along the channel reach, $A = A(x,t)$ is the channel cross-section area, $Q = Q(x,t)$ is the flow rate and $q = q(x,t)$ is the lateral inflow per unit length. Writing

equation (2) in the form

$$\frac{\partial A}{\partial t} = q - \frac{\partial Q}{\partial x}$$

and integrating each side with respect to s from x to $x+\Delta x$ over a channel reach Δx , it follows that

$$\begin{aligned} \int_x^{x+\Delta x} \frac{\partial A(s,t)}{\partial t} ds &= - \int_x^{x+\Delta x} \frac{\partial Q(s,t)}{\partial x} ds + \int_x^{x+\Delta x} q(s,t) ds \\ &= Q(x,t) - Q(x+\Delta x,t) + \int_x^{x+\Delta x} q(s,t) ds \end{aligned} \quad (3)$$

Now, assuming in equation (3) that integration and differentiation can be interchanged, which should be the case for these physically continuous functions, at least not near a strong shock, let

$$\frac{dS(t)}{dt} = \frac{\partial}{\partial t} \int_x^{x+\Delta x} A(s,t) ds$$

where $S(t)$ is the volume of water in the river reach from x to $x+\Delta x$ at time t , so it follows that

$$\frac{dS(t)}{dt} = Q(x,t) - Q(x+\Delta x,t) + \int_x^{x+\Delta x} q(s,t) ds \quad (4)$$

Equation (4) is the continuity equation (2) described as a macroscopic mass balance. Equation (4) is often used as the starting place to

develop a finite difference type approximation for water routing as in the Muskingum method as in Weinmann and Laurenson [1979] .

Integrating each side of equation (4) from time t_0 to time t and re-arranging the terms, the volume of water in the channel reach Δx at time t , $S(t)$, can be written in the form

$$\begin{aligned}
 S(t) &= \int_x^{x+\Delta x} A(s,t) ds \\
 &= \int_x^{x+\Delta x} A(s,t_0) ds + \int_{t_0}^t Q(x,w) dw - \int_{t_0}^t Q(x+\Delta x,w) dw \\
 &\quad + \int_{t_0}^t \int_x^{x+\Delta x} q(s,w) ds dw
 \end{aligned} \tag{5}$$

The values of the integrals in equation (5) will be approximated later by a choice of parameters. This then is the integral form of the water mass balance to be used herein.

The same procedure with the conditions about the river form can be used for material transport. Relative to the kinematic wave for water, the mass balance for a dissolved material such as orthophosphate or suspended material such as total phosphorus in open channel is given by

$$\frac{\partial (AC)}{\partial t} + \frac{\partial (QC)}{\partial x} = qC_i \tag{6}$$

where $C = C(x,t)$ is the concentration at x and time t on the channel reach and $C_i = C_i(x,t)$ is the lateral inflow concentration of

the lateral inflow q per unit length.

Equation (6) is of a form similar to that of equation (2). To solve equation (6) for the concentration, C_i , and q must be supplied as input functions, Q and A must be obtained from the water mass balance or be known and boundary conditions must be given. Again an integral form of this equation will be obtained, following the procedure used to obtain the integral form of the water mass balance in equation (4). From the material mass balance given by equation (6) an expression for the total mass, $\bar{S}(t)$, at time t over a channel reach from x to $x+\Delta x$ can be obtained where

$$\bar{S}(t) = \int_x^{x+\Delta x} A(s,t)C(s,t)ds$$

and

$$\frac{d\bar{S}(t)}{dt} = Q(x,t)C(x,t) - Q(x+\Delta x,t)C(x+\Delta x,t) + \int_x^{x+\Delta x} q(s,t)C_i(s,t)ds$$

from which

$$\begin{aligned} \bar{S}(t) &= \int_x^{x+\Delta x} A(s,t)C(s,t)ds \\ &= \int_x^{x+\Delta x} A(s,t_0)C(s,t_0)ds + \int_{t_0}^t Q(x,w)C(x,w)dw \\ &\quad - \int_{t_0}^t Q(x+\Delta x,w)C(x+\Delta x,w)dw + \int_{t_0}^t \int_x^{x+\Delta x} q(s,w)C_i(s,w)dsdw \end{aligned} \quad (7)$$

Equation (7) is then an integral form of the material mass balance. It will be used in the following approximation schemes.

Equations (5) and (7) will be the main equations used in developing predictive water quality models for storm events. We will look at methods to approximate these equations, at procedures to relate Q to A and to estimate q and C_p . The following sections will consider these problems.

METHOD OF APPROXIMATION

The goal of this section is to develop approximations of equations (5) and (7) with second order accuracy to the flow Q or concentration C at the downstream location using information from the upstream hydrograph, unmeasured lateral inflow and the Q vs A curve. The integrals given by equations (5) and (7) will be approximated to third order accuracy by use of parameters and intervals of length Δx and $\Delta t = t - t_0$ where by the parameters can be estimated from the available data.

In a previous paper [1981] the authors consider methods of approximation of equation (5) for water routing. The method of approximation is based on the following, applied here to a function $h(x)$ of one variable with at least second order derivatives on an interval from x_0 to x_1 using Taylors theorem. The function $h(x)$ can be written in the form

$$\begin{aligned} h(x) &= \alpha h(x) + (1 - \alpha)h(x) \\ &= \alpha [h(x_0) + h'(x_0)(x - x_0) + h''(\bar{x}_0)(x - x_0)^2/2] \\ &\quad + (1 - \alpha)[h(x_1) + h'(x_1)(x - x_1) + h''(\bar{x}_1)(x - x_1)^2/2] \end{aligned}$$

$$\begin{aligned}
&= \alpha[h(x_0) + h'(x_0)(x - x_0)] + (1 - \alpha)[h(x_1) + h'(x_1)(x - x_1)] \\
&\quad + [\alpha h''(\bar{x}_0)(x - x_0)^2 + (1 - \alpha)h''(\bar{x}_1)(x - x_1)^2]/2
\end{aligned} \tag{8}$$

where \bar{x}_0 , \bar{x}_1 are between x_0 and x and x and x_1 , respectively, depending on x .

Now integrate each side of equation (8) from x_0 to x_1 , simplify, use the mean-value theorem for integrals to simplify the remainder term,

$$\begin{aligned}
\int_{x_0}^{x_1} h(x) dx &= [\alpha h(x_0) + (1 - \alpha)h(x_1)]\Delta x + [\alpha h'(x_0) - (1 - \alpha)h'(x_1)](\Delta x)^2/2 \\
&\quad + O((\Delta x)^2)
\end{aligned} \tag{9}$$

where $\Delta x = x_1 - x_0$. The details for the approximation given by equation (9) are given by the authors in [1981]. Equation (9) simplifies to the trapezoidal rule for integration for the special case of $\alpha = 1/2$. The above form of approximation will be used to express each of the integrals in equations (5) and (7) in terms of parameters α, β , and ψ similar to what has been done above in equation (9). α, β , and ψ will then be chosen so that the terms involving the derivatives will be of order $(\Delta x)^3$. In equation (9) taking $\alpha = 1/2$ forces the term involving the derivative to be of order $(\Delta x)^3$, other choices for α are possible if additional properties of $h(x)$ are known.

Equation (5), for the water volume in the channel reach Δx , can then be written in the form

$$\begin{aligned}
S(t) &= [\alpha A(x,t) + (1 - \alpha)A(x+\Delta x,t)]\Delta x \\
&\quad + \left[\alpha \frac{\partial A(x,t)}{\partial x} - (1 - \alpha) \frac{\partial A(x+\Delta x,t)}{\partial x} \right] (\Delta x)^2/2 \\
&= [\alpha A(x,t_0) + (1 - \alpha)A(x+\Delta x,t_0)]\Delta x \\
&\quad + \left[\alpha \frac{\partial A(x,t_0)}{\partial x} - (1 - \alpha) \frac{\partial A(x+\Delta x,t_0)}{\partial x} \right] (\Delta x)^2/2 \\
&\quad + [BQ(x,t_0) + (1 - B)Q(x,t)]\Delta t \\
&\quad + \left[B \frac{\partial Q(x,t_0)}{\partial t} - (1 - B) \frac{\partial Q(x,t)}{\partial t} \right] (\Delta t)^2/2 \\
&\quad - [\psi Q(x+\Delta x,t_0) + (1 - \psi)Q(x+\Delta x,t)]\Delta t \\
&\quad - \left[\psi \frac{\partial Q(x+\Delta x,t_0)}{\partial t} - (1 - \psi) \frac{\partial Q(x+\Delta x,t)}{\partial t} \right] (\Delta t)^2/2 \\
&\quad + \int_{t_0}^t \int_x^{x+\Delta x} q(s,w) ds dw + O((\Delta x)^3)
\end{aligned} \tag{10}$$

where $\Delta x = k\Delta t$ for some constant k and α, β , and ψ are arbitrary. α, β , and ψ are determined so as to increase the order of the terms involving the partial derivatives to order $(\Delta x)^3$, such choice is not unique and will be chosen to depend on the knowledge of the Q vs A curve at the upstream location.

In [1981] the authors write $A(x+\Delta x,t)$ and $A(x+\Delta x,t_0)$ in terms of $Q(x,t)$, $Q(x,t_0)$, $Q(x+\Delta x,t)$ and $Q(x+\Delta x,t_0)$ substitute into equation (10) and simplify where $\Delta t = K = \Delta x/f'(A(x,t_0))$ yielding an expression similar in form to that of the Muskingum method for water routing. The choice for K , the time parameter is the same choice as is often used in the Muskingum method for water routing as has been noted by Cunge [1969] and Nash [1959].

Equation (10) with the above change can then be written in the form,
after re-arranging the terms

$$\begin{aligned}
 & K[\alpha Q(x,t) + (1 - \alpha)Q(x+\Delta x,t)] - K[\alpha Q(x,t_0) + (1 - \alpha)Q(x+\Delta x,t_0)] \\
 & + [\alpha(\frac{\partial A(x,t)}{\partial x} - \frac{\partial A(x,t_0)}{\partial x}) - (1 - \alpha)(\frac{\partial A(x+\Delta x,t)}{\partial x} - \frac{\partial A(x+\Delta x,t_0)}{\partial x})](\Delta x)^2/2 \\
 = & K[\beta Q(x,t_0) + (1 - \beta)Q(x,t)] + [\beta\frac{\partial Q(x,t_0)}{\partial t} - (1 - \beta)\frac{\partial Q(x,t)}{\partial t}](\Delta t)^2/2 \\
 & - [\psi Q(x+\Delta x,t_0) + (1 - \psi)Q(x+\Delta x,t)]K \\
 & - [\psi\frac{\partial Q(x+\Delta x,t_0)}{\partial t} - (1 - \psi)\frac{\partial Q(x+\Delta x,t)}{\partial t}](\Delta t)^2/2 \\
 & + \int_{t_0}^t \int_x^{x+\Delta x} q(s,w)dsdw + O((\Delta x)^3) \tag{11}
 \end{aligned}$$

Solving for $Q(x+\Delta x,t)$, the flow rate at the downstream location at
time t , equation (11) can be re-written in the form

$$\begin{aligned}
 Q(x+\Delta x,t) = & \left[\frac{1 - \alpha - \beta}{2 - \alpha - \psi} \right] Q(x,t) + \left[\frac{\alpha + \beta}{2 - \alpha - \psi} \right] Q(x,t_0) + \left[\frac{1 - \alpha - \psi}{2 - \alpha - \psi} \right] Q(x+\Delta x,t_0) \\
 & + \left\{ [\beta\frac{\partial Q(x,t_0)}{\partial t} - (1 - \beta)\frac{\partial Q(x,t)}{\partial t} - \psi\frac{\partial Q(x+\Delta x,t_0)}{\partial t} \right. \\
 & + (1 - \psi)\frac{\partial Q(x+\Delta x,t)}{\partial t}](\Delta t)^2 \\
 & + [-\alpha(\frac{\partial A(x,t)}{\partial x} - \frac{\partial A(x,t_0)}{\partial x}) + (1 - \alpha)(\frac{\partial A(x+\Delta x,t)}{\partial x} \\
 & - \frac{\partial A(x+\Delta x,t_0)}{\partial x})](\Delta x)^2 \Big\} / 2K(2 - \alpha - \psi) \\
 & + \int_{t_0}^t \int_x^{x+\Delta x} q(s,w)dsdw / K(2 - \alpha - \psi) + O((\Delta x)^2) \tag{12}
 \end{aligned}$$

In equation (11) or (12) the parameters α , β , and ψ are to be chosen so that the order of the terms involving the partial derivative terms is increased, this can be done with any one of several possible choices for α , β , and ψ . To avoid computing with $Q(x+\Delta x, t_0)$, data dependent on knowledge of the new downstream computed data, one choice is to take $\alpha = 1 - \psi$. In [1981] the authors show that $\alpha = \beta = 1 - \psi$ is such a choice where $\alpha = f'(A(x, t_0))/2f'(A(x, t))$. This choice for α can be computed from the upstream data and knowledge of the Q vs A curve at the upstream location, so here we have α as a function of the wave velocity at the upstream location. Thus, in equation (12), the downstream flow rate, $Q(x+\Delta x, t)$, can be predicted from knowledge of or previously computed upstream flow rates $Q(x, t)$ and $Q(x, t_0)$ and knowledge of the Q vs A curve at the upstream location. With the above choice for α , β , and ψ equation (12) has the form

$$Q(x+\Delta x, t) = (1 - 2\alpha)Q(x, t) + 2\alpha Q(x, t_0) + \int_{t_0}^t \int_x^{x+\Delta x} q(s, w) ds dw + O((\Delta x)^2) \quad (13)$$

In a manner similar to the procedure used to obtain an approximation for the downstream flow rate from knowledge of the upstream flow rate and the upstream Q vs A curve an approximation for the downstream concentration C at some time t can be obtained from knowledge of the upstream flow rate, cross-section area of the channel and the Q vs A curve. From equation (9), the material mass balance given by the integral form of equation (7) and in terms of the (new) parameters α , β , and ψ , to be chosen, can be written as

$$\begin{aligned}
\bar{S}(t) &= \Delta x [\alpha A(x,t)C(x,t) + (1 - \alpha)A(x+\Delta x,t)C(x+\Delta x,t)] \\
&\quad + [\alpha \frac{\partial(A(x,t)C(x,t))}{\partial x} - (1 - \alpha) \frac{\partial(A(x+\Delta x,t)C(x+\Delta x,t))}{\partial x}] (\Delta x)^2/2 \\
&= \Delta x [\alpha A(x,t_0)C(x,t_0) + (1 - \alpha)A(x+\Delta x,t_0)C(x+\Delta x,t_0)] \\
&\quad + [\alpha \frac{\partial(A(x,t_0)C(x,t_0))}{\partial x} - (1 - \alpha) \frac{\partial(A(x+\Delta x,t_0)C(x+\Delta x,t_0))}{\partial x}] (\Delta x)^2/2 \\
&\quad + \Delta t [BQ(x,t_0)C(x,t_0) + (1 - B)Q(x,t)C(x,t)] \\
&\quad + [B \frac{\partial(Q(x,t_0)C(x,t_0))}{\partial t} - (1 - B) \frac{\partial(Q(x,t)C(x,t))}{\partial t}] (\Delta t)^2/2 \\
&\quad - \Delta t [\psi Q(x+\Delta x,t_0)C(x+\Delta x,t_0) + (1 - \psi)Q(x+\Delta x,t)C(x+\Delta x,t)] \\
&\quad - [\psi \frac{\partial(Q(x+\Delta x,t_0)C(x+\Delta x,t_0))}{\partial t} - (1 - \psi) \frac{\partial(Q(x+\Delta x,t)C(x+\Delta x,t))}{\partial t}] (\Delta t)^2/2 \\
&\quad + \int_{t_0}^t \int_x^{x+\Delta x} q(s,w) C_i(s,w) ds dw + O((\Delta x)^3) \tag{14}
\end{aligned}$$

As previously noted for water routing, chose $\Delta x = f'(A(x,t_0))\Delta t$ so that time and distance are related to the wave velocity. Now to obtain a form of approximation similar to that of equation (12) from equation (14), solve equation (14) for $C(x+\Delta x,t)$, the downstream concentration. From the form for $C(x+\Delta x,t)$ the routing parameters α , B , and ψ will be determined. α will be determined so as to be a function of the wave velocity of the flow relative to the Q vs A curve and the upstream and downstream hydrograph for water.

For convenience, let $f'(A(x, t_0)) = W$ and
 $(1 - \alpha)WA(x+\Delta x, t) + (1 - \psi)Q(x+\Delta x, t) = D$, solve equation (14) for
 $C(x+\Delta x, t)$, giving the form

$$\begin{aligned}
 C(x+\Delta x, t) = & [-\alpha WA(x, t) + (1 - \beta)Q(x, t)]C(x, t)/D \\
 & + [\alpha WA(x, t_0) + \beta Q(x, t_0)]C(x, t_0)/D \\
 & + [-\psi Q(x+\Delta x, t_0) + (1 - \alpha)WA(x+\Delta x, t_0)]C(x+\Delta x, t_0)/D \\
 & + \left\{ \left[-\alpha \left(\frac{\partial(A(x, t)C(x, t))}{\partial x} \right) - \frac{\partial(A(x, t_0)C(x, t_0))}{\partial x} \right] \right. \\
 & + (1 - \alpha) \left(\frac{\partial(A(x+\Delta x, t)C(x+\Delta x, t))}{\partial x} \right. \\
 & \quad \left. \left. - \frac{\partial(A(x+\Delta x, t_0)C(x+\Delta x, t_0))}{\partial x} \right) \right] W \Delta x \\
 & + \left[\beta \frac{\partial(Q(x, t_0)C(x, t_0))}{\partial t} - \psi \frac{\partial(Q(x+\Delta x, t_0)C(x+\Delta x, t_0))}{\partial t} \right. \\
 & \quad - (1 - \beta) \frac{\partial(Q(x, t_0)C(x, t_0))}{\partial t} \\
 & \quad \left. + (1 - \psi) \frac{\partial(Q(x+\Delta x, t)C(x+\Delta x, t))}{\partial t} \right] \Delta t \Big\} / 2D \\
 & + \int_0^t \int_x^{x+\Delta x} q(s, w) C_1(s, w) ds dw / D \Delta t + O((\Delta x)^2) \quad (15)
 \end{aligned}$$

In equation (15) force the coefficient of $C(x+\Delta x, t_0)$ to be zero or to contribute an error of order $(\Delta x)^2$ so as to avoid computing with downstream concentration data. Here the choice is made so that

$$-\psi Q(x+\Delta x, t_0) + (1 - \alpha)WA(x+\Delta x, t_0) = 0. \quad (16)$$

In equation (16) the choice for α and ψ is not unique. Here let $\alpha = \psi$ as one possible choice and solve equation (16) for α giving

$$\alpha = \frac{WA(x+\Delta x, t_0)}{WA(x+\Delta x, t_0) + Q(x+\Delta x, t_0)}$$

$$= \frac{W}{W + v_0} \quad (17)$$

where $v_0 = Q(x+\Delta x, t_0)/A(x+\Delta x, t_0)$ is the water velocity of the hydrograph at the downstream location and time $(x+\Delta x, t_0)$, where also the flow, $Q(x+\Delta x, t_0)$, is previously calculated by a water routing method such as that given by equation (13). Also the channel cross-section area, $A(x+\Delta x, t_0)$, can be calculated from knowledge of the Q vs A curve at $x+\Delta x$ on the channel reach.

The choice of the parameters α , β , and ψ is also made so that in equation (15) the dependence on the partial derivative terms is of order $(\Delta x)^2$. There are again many ways of satisfying equation (16) and also forcing the partial derivative terms in equation (15) to be of order $(\Delta x)^2$.

For the choice of $\alpha = \beta = \psi$, equation (15), for the downstream concentration, has the form

$$C(x+\Delta x, t) = ((1 - \alpha)Q(x, t) - WA(x, t))C(x, t)/D$$

$$+ \alpha(WA(x, t_0) + Q(x, t_0))C(x, t_0)/D$$

$$+ \int_{t_0}^t \int_x^{x+\Delta x} q(s, w)C_i(s, w)dsdw/D\Delta t + O((\Delta x)^2) \quad (18)$$

A second choice for the routing parameters, $\alpha = \psi = 1 - \beta$ and the same choice for α , as given by equation (17), so that equation (15)

can be written in the form

$$\begin{aligned}
 C(x+\Delta x, t) = & \alpha(Q(x, t) - WA(x, t))C(x, t)/D \\
 & + (\alpha WA(x, t_0) + (1 - \alpha)Q(x, t_0))C(x, t_0)/D \\
 & + \int_{t_0}^t \int_x^{x+\Delta x} q(s, w) C_i(s, w) ds dw / D \Delta t + O((\Delta x)^2) \quad (19)
 \end{aligned}$$

In the next section a discussion of how the integrals representing the lateral inflow and lateral inflow concentration might be approximated. This information is necessary in equations (13), (18), and (19).

UNMEASURED INFLOW

In equation (13), to predict the downstream flow rate $Q(x+\Delta x, t)$, or equation (19), to predict the downstream material concentration $C(x+\Delta x, t)$, knowledge of the amount of unmeasured lateral inflow q and the amount of unmeasured lateral inflow concentration C_i is required, both relative to the location on the stream reach x and the time t . The amount of unmeasured lateral water inflow or the material concentration in the lateral inflow over a given channel reach for a storm event can be estimated with some knowledge of the river basin. This knowledge includes water flow and material concentration for storm events occurring at a similar time of year and with a similar intensity and duration. In the following discussion a method will be developed which can give an indication of when, relative to time and the knowledge of the upstream hydrograph, the relative amount of available unmeasured inflow should be added to the computed downstream hydrograph. It will be assumed that the unmeasured material concentration C_i is carried with the unmeasured water inflow q . In the following discussion it will be noted that the largest contribution of the unmeasured inflow q to changes in the downstream hydrograph at a position x on the channel reach when compared to the upstream hydrograph at position $x+\Delta x$ on the channel reach will occur in time after the peak in the hydrograph at x . Knowledge of q then allows an approximation for the integrals in equations (13), (18) or (19). That this is reasonable follows by re-writing the form of the momentum equation for open channel flow and comparing q with the slope of the free water surface under some steady state conditions.

The momentum equation for open channel flow, Stoker [1957], can be written in the form

$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} + \frac{fLv^2}{A} - gs + \frac{1}{A}(v - u_x)q = 0 \quad (20)$$

where v is the water velocity, s is the slope of the free water surface (positive downward for positive downstream channel distance), f the friction force, L the wetted perimeter of the channel bed and u_x the component of the velocity of the lateral water inflow q in the downstream direction.

With the assumption that $\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x}$ is small or zero, that is over a short channel reach x to $x+\Delta x$ and small change in time, the change in the velocity of the water is negligible (velocity constant), equation (20) can then be solved for the lateral inflow $q = (gsA - fLv^2)/(v - u_x)$. For unmeasured lateral inflow q , assume that the component $u_x = 0$ for the component of the velocity of the lateral inflow q in the downstream direction, so that

$$q = \frac{gsA - fLv^2}{v} \quad (21)$$

Now a relationship between the lateral inflow q and the slope of the free water surface s will be obtained with the assumption that there is a steady state condition for v near the peak of the wave at time t fixed over the channel reach (peak in the wave in the channel reach x direction). Also g and f are assumed to be constant and $q > 0$. Near the peak of the wave there are points in the x direction on either side of the peak where the cross-section areas of the channel bed

and also the wetted perimeters are the same. Suppose that at these two respective points the lateral inflows are q_1 and q_2 , such that $q_2 > q_1$.

Let $s = s_0 - \frac{\partial y}{\partial x}$, where s_0 is the slope of the channel bed and y is the river stage. Let y_1 and y_2 be the river stage corresponding to q_1 and q_2 respectively. From equation (21)

$$\frac{g(s_0 - \frac{\partial y_1}{\partial x})A - fLv^2}{v} > \frac{g(s_0 - \frac{\partial y_2}{\partial x})A - fLv^2}{v}$$

implies that $\frac{\partial y_1}{\partial x} > \frac{\partial y_2}{\partial x}$ and since, relative to the positive channel reach x direction, for $\frac{\partial y}{\partial x} > 0$ the water wave is increasing over the channel reach as occurs behind the peak over the channel reach and for $\frac{\partial y}{\partial x} < 0$ the water wave stage is decreasing over the channel reach as occurs before the peak over the channel reach. Thus it follows that near the peak, with the above assumptions on v, A, L , and f , $q_2 > q_1$ implies that $\frac{\partial y_1}{\partial x} > \frac{\partial y_2}{\partial x}$, so q_2 occurs before the peak in the wave in the x direction and q_1 occurs after the peak of the wave in the x direction along the channel reach. With the same assumptions on v, A, L and f , it also follows that $\frac{\partial y_1}{\partial x} > \frac{\partial y_2}{\partial x}$ implies $q_2 > q_1$. Thus larger lateral inflow occurs before the peak in the wave in the downstream x direction for the same cross-section area A (or Q) occurring before and after the peak with the steady state assumption on v . Generally, for rivers, $\frac{\partial y_1}{\partial x} > \frac{\partial y_2}{\partial x}$ implies that $\frac{\partial Q_1}{\partial x} > \frac{\partial Q_2}{\partial x}$ for corresponding flow rates Q_1 and Q_2 .

Now from the continuity equation (2), where $\frac{\partial A}{\partial t} = \frac{\partial Q}{\partial t} / \frac{dQ}{dA}$ and with

assumption as above on the lateral inflow q it follows that, from

$$q_2 = \frac{1}{\frac{dQ_2}{dA}} \frac{\partial Q_2}{\partial t} + \frac{\partial Q_2}{\partial x}$$

where $\frac{\partial Q_2}{\partial x}$ is negative, $\frac{dQ_2}{dA}$ is positive and q_2 is positive, then $\frac{\partial Q_2}{\partial t}$ is positive, which occurs after the peak in the positive t direction in the hydrograph at position x on the channel reach. In a similar manner to the above for Q_1 ,

$$q_1 - \frac{\partial Q_1}{\partial x} = \frac{1}{\frac{dQ_1}{dA}} \frac{\partial Q_1}{\partial t}$$

where $\frac{\partial Q_1}{\partial x}$ is positive, q_1 is positive and for rivers that q_1 is smaller than $\frac{\partial Q_1}{\partial x}$ it follows that $\frac{\partial Q_1}{\partial t}$ is negative, which occurs before the peak in the hydrograph at position x on the channel reach.

The above discussion indicates that relative to the peak of a hydrograph at a point x on the channel reach the relative amount of unmeasured inflow q is higher after the peak at x in time t than before the peak at x in time t .

IMPLEMENTATION

In this section a discussion of how the approximations given by equations (13), (18), or (19) can be implemented so as to compute $Q(x+\Delta x, t)$ and $C(x+\Delta x, t)$, the predicted flow rate and material concentration at a downstream location with channel reach Δx . To compute both the predicted flow and material concentration knowledge of the upstream hydrograph from either a given curve or from actual flow and concentration measurement data is needed. Also knowledge of the Q vs A curve or measurement data is required both at the upstream and downstream measurement stations (here assumed to be single valued). To compute $Q(x+\Delta x, t)$ it is necessary to obtain an earlier time t_0 .

Suppose the upstream measuring station is at $x = 0$ on the channel reach. At $x = 0$ the initial flow, $Q(0, t_j)$ and concentration $C(0, t_j)$ is known at times $t_1, t_2, t_3, \dots, t_k$ (times not necessary to be equally spaced). The downstream hydrograph at $x = L$ will be obtained by first obtaining the predicted hydrograph at point on the channel reach between 0 and L so that the relative length of Δx and the channel length L , $\Delta x/L$, is less than 1 (the channel reach length L can be scaled to length 1 if desired). The channel reach of length L is partitioned into N subintervals (not necessary to be equally spaced), here of length L/N , so that $\Delta x = L/N$.

The partition of the channel reach can be chosen so as to locate a point on the reach from 0 to L pertaining to the mouth of a tributary at which measured inflow data is known. Relative to the computed hydrograph from the main branch of the river and knowledge of

the hydrograph of the tributary there is a juncture problem at this location on the channel reach. For a tributary with flow rate not differing greatly from that of the main stream of interest the tributary can be treated as a point source.

The Q vs A curves are computed at points x and $x+\Delta x$ between 0 and L on the channel reach, with the assumption that the river channel characteristics change slowly from 0 to L so that linear interpolation can be used to obtain an approximation to the Q vs A curves at x and $x+\Delta x$ ($\frac{dQ}{dA}$ also is approximated from the Q vs A curves). The needed values of $\frac{dQ}{dA} = f'(A)$, Q , and A for equations (13), (18), and (19) can then be approximated from the constructed Q vs A curves at x and $x+\Delta x$ on the channel reach.

Now with the channel reach from 0 to L partitioned into N subintervals and taking $x_j = jL/N$ as a point on the channel reach where the hydrograph is known, has been computed. Equation (13) then is used to compute the hydrograph at $x_{j+1} = (j+1)L/N$; the following will outline the procedure. Suppose at x_j the predicted hydrograph has been computed at times $t_1, t_2, t_3, \dots, t_k$ so that $Q(x_j, t_1)$, $Q(x_j, t_2)$, \dots , $Q(x_j, t_k)$ and $C(x_j, t_1)$, $C(x_j, t_2)$, \dots , $C(x_j, t_k)$ are known. To use equation (13) to compute $Q(x_{j+1}, t_i)$ where $Q(x_{j+1}, t_1)$, $Q(x_{j+1}, t_2)$, \dots , $Q(x_{j+1}, t_{i-1})$ have been previously calculated, it is necessary to first obtain the time t_{i0} , $f'(A(x_j, t_{i0}))$, and $f'(A(x_j, t_i))$. Time t_{i0} can be obtained by iteration and since from $Q(x_j, t_{i-1})$ to $Q(x_j, t_i)$ linear interpolation is to be used, it is

sufficient to compute $A(x_j, t_i)$ and $\Delta \bar{t} = \Delta x / f'(A(x_j, t_i))$ from the Q vs A curve at x_j , take an approximation for t_{10} as $\bar{t}_{10} = t_i - \Delta \bar{t}$ then compute $A(x_j, \bar{t}_{10})$, $\Delta t^* = \Delta x / f'(A(x_j, \bar{t}_{10}))$ and take $t_{10} = t_i - (\Delta \bar{t} + \Delta t^*)/2$. Note that at t_1 , the first recorded measurement time on the hydrograph at x_j , to compute t_{10} where $t_{10} \leq t_1$, use linear interpolation from $Q(x_j, t_1)$ to $Q(x_j, t_2)$ and extend this straight line approximation to values less than t_1 so that t_{10} can be computed as previously.

Once t_{10} is computed then $\alpha = f'(A(x_j, t_{10})) / 2f'(A(x_j, t_i))$ can be computed for equation (13) so that $Q(x_{j+1}, t_i)$ can be computed with a correction to be given for the unmeasured lateral inflow q . To approximate the term for the lateral inflow, as noted in the previous section, relative to the hydrograph at x_j , the inflow for water is accumulated when the hydrograph is increasing in Q for increasing time, with a small percentage of the accumulated inflow added to the computed Q and the inflow is treated as in equation (13) when the hydrograph is decreasing in Q for increasing time. For example, if the hydrograph at x_j begins increasing at time t_m and is also increasing at time t_{m+1} then the accumulation (storage) $\bar{A}d_m$ at t_m is $\bar{A}d_m = q(x_j, t_m) \Delta x$ so that $f/qdsdw/K = r\bar{A}d_m$ and take a new $\bar{A}d_m = (1 - r)\bar{A}d_m$. Since the hydrograph is also increasing at $Q(x_j, t_{m+1})$ take $\bar{A}d_{m+1} = \bar{A}d_m + q(x_j, t_{m+1}) \Delta x$ and repeat what was done previously for $\bar{A}d_m$. In this way much of the lateral inflow, when the hydrograph at x_j is increasing, is stored until the hydrograph changes from increasing to decreasing in flow rate Q as the time t increases. In the examples

of the next section the parameter r was chosen to be .05. Note that when the hydrograph is decreasing $\bar{A}d_m = \iint q ds dw / K$.

Once $Q(x_{j+1}, t_i)$ is determined from equation (13) there is sufficient information to compute $C(x_{j+1}, t_i)$. The knowledge of the Q vs A curve at the downstream location permits calculation of $A(x_{j+1}, t_i)$, $A(x_{j+1}, t_i)$, and $\alpha = f'(A(x_j, t_{i0})) / (f'(A(x_j, t_{i0})) + v_o)$ where $v_o = Q(x_{j+1}, t_{i0}) / A(x_{j+1}, t_{i0})$ needed for equation (18) or equation (19). $C(x_{j+1}, t_i)$ is then corrected for the lateral inflow concentration using the information with regard to the lateral water inflow. As for the water above a new $C(x_j, t_m)$ is computed from $C(x_j, t_m)$ as new $C(x_j, t_m) = (Q(x_j, t_m)C(x_j, t_m) + \bar{C}A(x_j, t_m)\bar{A}d_m) / (Q(x_j, t_m) + \bar{A}d_m)$ where $\bar{C}A(x_j, t_m)$ is the concentration of the accumulated lateral inflow. Then take new $\bar{C}A(x_j, t_m) = \text{new } C(x_j, t_m)$ so that the routed water and the lateral inflow accumulation is mixed before routing to $x+\Delta x$ downstream. Note that the integral

$$\int_{t_0}^t \int_x^{x+\Delta x} C_i(s, w) q(s, w) ds dw$$

will be approximated from the upstream data only, and will be taken to be $C_i(x, t)q(x, t)\Delta x \Delta t$ in this discussion. For the portion of the accumulated flow added when the hydrograph is decreasing in Q for increasing time t in equation (18) or (19) use $\iint C_i q ds dw / D = C_i(x_j, t_i)q(x_j, t_i)\Delta x \Delta t / D$. Here $q(x_j, t_i)\Delta x$ is $\bar{A}d_i$ to be compatible with the previous notation.

A further discussion of some of the above will be continued in the next section when the computed results of a flow and concentration are

given for a particular example of a reach of the Upper Sandusky River in Ohio.

STORM EVENTS

In this section the numerical approximations of the mass balance equations in the integral form (equations (13) and (19)) and the method of treating the unmeasured inflow was implemented using data available from the USACOE [1978] on the Sandusky River (Ohio).

The 33 mile river reach from the measurement station near Bucyrus to the measurement station near Upper Sandusky has a tributary, Broken Sword Creek, with a measurement station at Nevada. The mouth of the tributary was about 16.2 miles from the upstream measurement station at Upper Sandusky. The total river basin area above the Upper Sandusky measurement station was 298 square miles with 88.8 square miles accounted for by the Sandusky River basin above the Bucyrus measurement station and 83.8 square miles accounted for above the Broken Sword Creek measurement station on the tributary. This leaves 125.4 square miles of drainage area with unmeasured inflow. The unmeasured lateral inflow area along the 33 mile river reach was approximated by a trapazodial area roughly matching the geometry of the river basin. This total area then was partitioned for each Δx on the stream reach based upon the percentage of the trapazodial area which would drain into this Δx of river. The percentage of available area apportioned to stream reach Δx was then multiplied by the estimated amount of total available unmeasured inflow for the unmeasured drainage area to obtain the

unmeasured inflow available for the channel reach from x to $x+\Delta x$.

This percentage was then used to approximate the value of the integrals

$$\int_{t_0}^t \int_x^{x+\Delta x} q(s,w) ds dw$$

and

$$\int_{t_0}^t \int_x^{x+\Delta x} C_1(s,w) q(s,w) ds dw$$

needed for equations (13) and (19) .

From the USACOE [1978] data two storm events were considered. For one storm event, data from 3/1/76 1300 hours to 3/10/76 1900 hours scaled so the initial time corresponds to time $t = 0$ and the final time corresponds to $t = 216$ (hour). During the time at the upstream measurement station (Bucyrus) when the hydrograph was changing most rapidly, the measurements in flow and concentration (specific conductance) were available in approximately 6 hour intervals. Similar data was available near the mouth of the tributary (Broken Sword Creek). The initial upstream data was interpolated linearly to obtain approximate measurements at three hour intervals from $t = 0$ to $t = 216$. Using the procedure suggested in (Gray [1973], section seven), the upstream hydrograph (Bucyrus) was used to estimate the duration of the storm event (111 hours), beginning at $t = 25.5$ and ending at $t = 136.5$. For the time period, $t = 25.5$ to $t = 136.5$, the intensity of the rainfall was assumed to be uniform over the unmeasured river basin area.

Since the downstream hydrograph was known a mass balance for water and and material (conductance) could be used in conjunction with data at

the upstream location (Bucyrus), the tributary, and the downstream measurement station (Upper Sandusky) to calculate the water and material inflow from the unmeasured area over the time $t = 0$ to $t = 216$. If the water flow and concentration at the downstream location are known, an estimate for the unmeasured lateral inflow might be obtained from the knowledge of previous storm events on the river basin for a corresponding time of year and storm duration. For this storm, from $t = 25.5$ to $t = 136.5$ the unmeasured inflow was estimated to be $428.2 \text{ ft}^3/\text{sec}$ over the entire 125.4 square mile river basin, so that the integral

$$\int_x^{x+\Delta x} q(s,t)ds$$

can be estimated to be 428.2 times the percentage of area available from x to $x+\Delta x$. Similar, by a mass balance on the specific conductance C_1 was estimated to be $389.9 \text{ } \mu\text{MHO}$. To account for the groundwater inflow during the periods of time 0 to 25.5 and 136.5 to 216 before and after the storm events the uniform inflow was estimated to be $70 \text{ ft}^3/\text{sec}$ and C_1 estimated to be $700 \text{ } \mu\text{MHO}$ based on available data before and after the storm event at the downstream location. To account for storage of unmeasured inflow when the hydrograph was rising, as discussed in the section on unmeasured inflow, the parameter r was chosen to be .05 (for r in the range .03 to .08 only small variations were noted in the location of the peak of the hydrograph at Upper Sandusky). The 33 mile channel reach was partitioned into 180 subreach distances of length 968 ft, as the choice for Δx .

The predicted hydrograph is given in Figure 2 for both the flow and specific conductance as well as the values of the measured data over the time at the downstream location. The accuracy of the numerical method was checked by integrating the mass balance over the whole storm for water predicted at the downstream measurement station and finding it to be 0.48 percent higher than the integrated inflow data indicated. Using the same procedure, the mass balance for specific conductance was 1.21 percent higher at Upper Sandusky than the actual inflow data indicated.

A second storm event over the same river reach has been considered. This storm event covered the time interval from 2/21/77 1900 hours to 3/3/77 1300 hours, a total time period of 234 hours. In this storm the storm duration has been estimated to be 111 hours, from $t = 31.5$ to $t = 142.5$.

For the period from $t = 31.5$ to $t = 142.5$ the unmeasured inflow rate, over the channel reach, was estimated to be $225.2 \text{ ft}^3/\text{sec}$ and the inflow concentration for specific conductance was estimated to be $814.2 \text{ } \mu\text{MH0}$. During the period from $t = 0$ to $t = 31.5$ the water inflow was estimated to be $130 \text{ ft}^3/\text{sec}$ over the channel reach and the specific conductance $900 \text{ } \mu\text{MH0}$. Also for the period $t = 142.5$ to $t = 234$, the inflow was estimated to be $40 \text{ ft}^3/\text{sec}$ for water and the specific conductance $900 \text{ } \mu\text{MH0}$ over the channel reach. The predicted hydrograph is given in Figure 3 for both the flow and specific conductance as well as the values of the measured data

over the time at the downstream location. The integrated mass balance for water at the downstream measurement station at Upper Sandusky was calculated to be 0.7 percent higher than the actual integrated flow indicated and 2.1 percent higher for specific conductance.

Remark: Both of the above examples were implimented using FORTRAN Level G. Also the CPU time for each example was about 10 seconds on a Amdahl 470 Model V/7A computer.

SUMMARY AND CONCLUSIONS

An approximation technique based on an integrated form of the mass balance for water flow and dissolved substances is developed. The parameters in this method of approximation are determined from knowledge of the Q vs A curve and are functions of the wave velocity and/or the water velocity. In terms of the flow Q or concentration C this approximation yields errors of order two; the order of error of the integral approximation is three.

An input element in the use of these mass balances is the estimation of the unmeasured inflow. At a point on the stream reach a relatively large amount of the unmeasured inflow is added to the hydrograph shortly after the peak in the water flow. This corresponds qualitatively to the discription of lateral inflow as obtained from the momentum equation under psuedo steady state conditions.

An algorithm was formulated based in these approximations and applied to water flow and conductance data from the Sandusky River in Ohio. The predicted water flow and conductivity at the downstream stations correspond

well with the measured values. Over various stream reaches the predicted total mass of water in a specified period of time was within one percent of the total mass of the water flowing into the stream reach during the same period of time. The theoretical mass balance on the conductivity was within two percent.

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LIST OF FIGURES

Figure 1. - Discharge Versus Area Curves for Stations in Sandusky River Basin at U.S. Geological Survey Stations (1 = Sandusky River near Pucyrus; 2 = Sandusky River near Upper Sandusky; 3 = Tymochtee Creek at Crawford; 4 = Sandusky River near Mexico; 5 = Sandusky River near Fremont)

Figure 2. - Hydrograph and Chemograph at U.S. Geological Survey Gaging Station on Sandusky River near Upper Sandusky, Ohio, for Storm Event 3/1/76 to 3/10/76

———— Predicted Hydrograph near Upper Sandusky
 x x x x x Measured Hydrograph near Upper Sandusky
 - - - - - Predicted Chemograph near Upper Sandusky
 Δ Δ Δ Δ Δ Measured Chemograph near Upper Sandusky

Figure 3. - Hydrograph and Chemograph at U.S. Geological Survey Gaging Station on Sandusky River near Upper Sandusky, Ohio, for Storm Event 2/21/77 to 3/3/77

———— Predicted Hydrograph near Upper Sandusky
 x x x x x Measured Hydrograph near Upper Sandusky
 - - - - - Predicted Chemograph near Upper Sandusky
 Δ Δ Δ Δ Δ Measured Chemograph near Upper Sandusky

Figure 1.

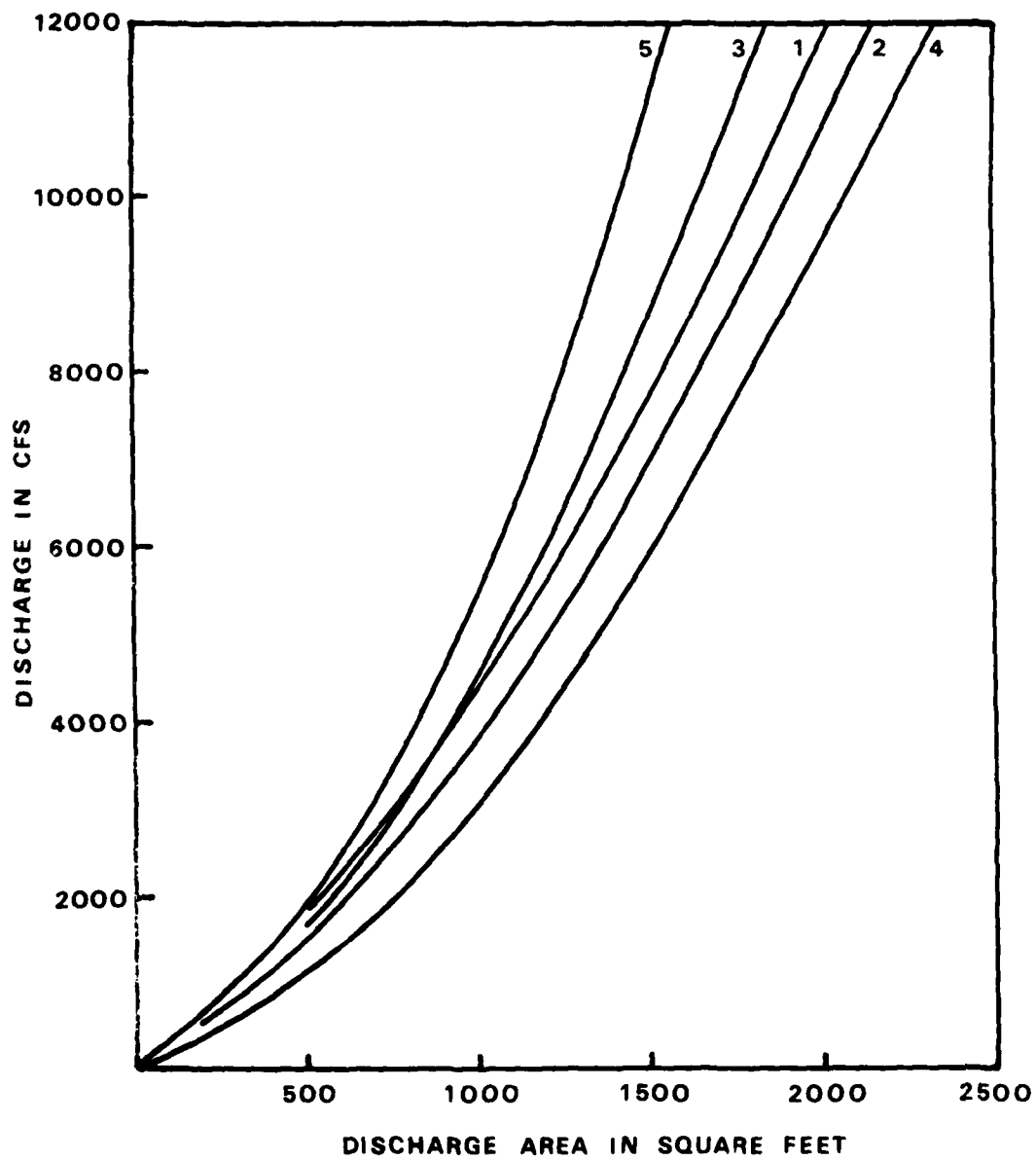


Figure 2.

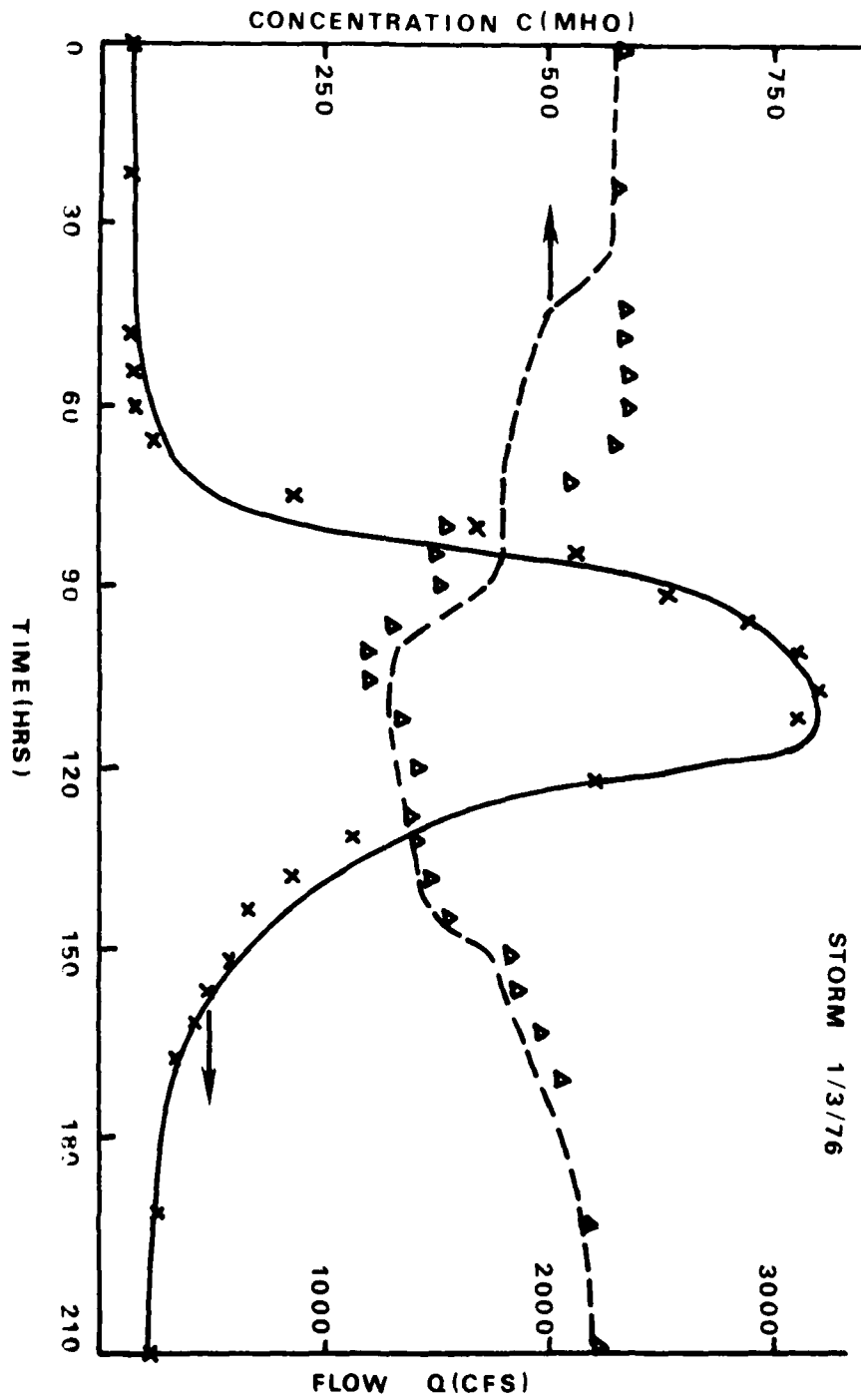
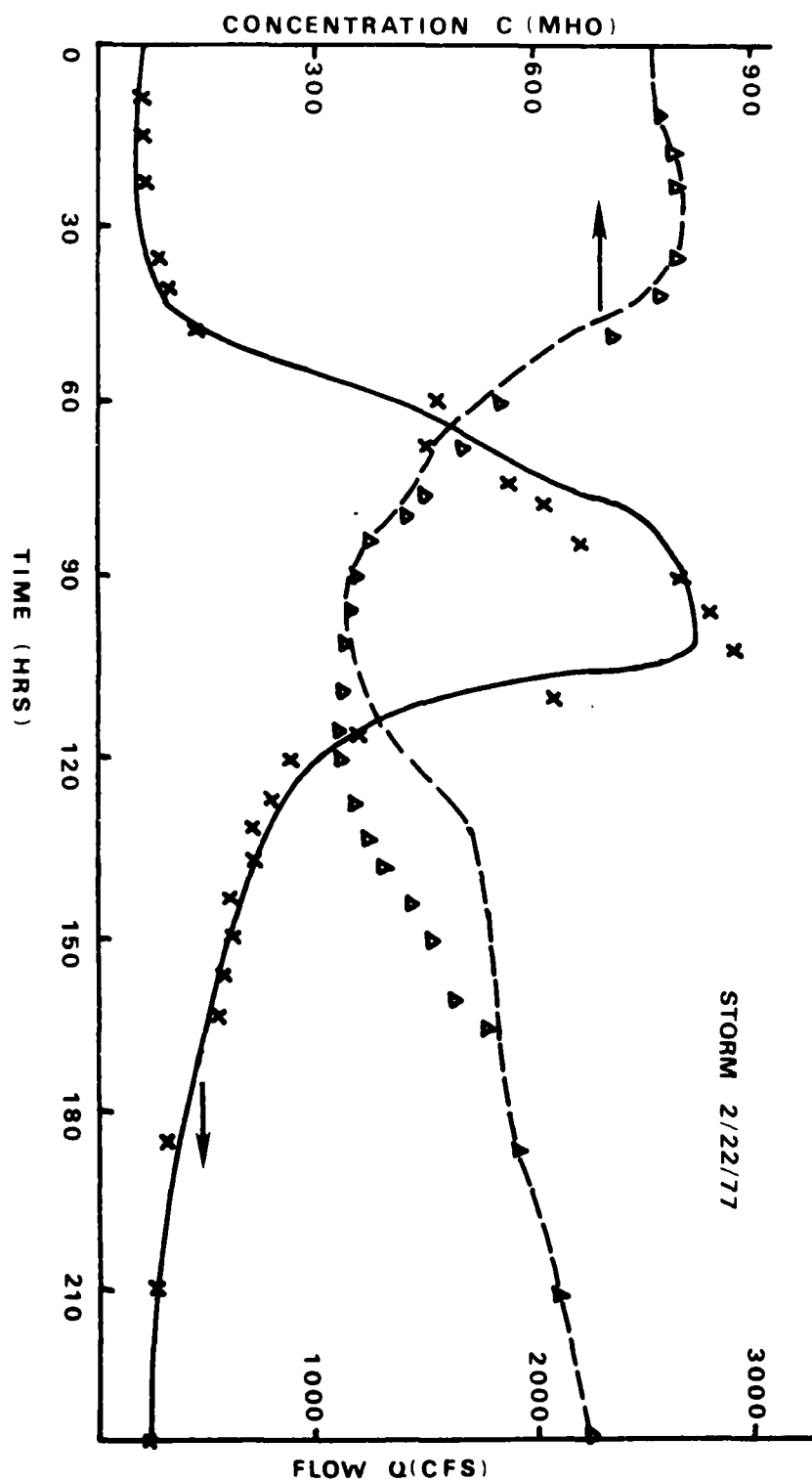


Figure 3.



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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report summarizes results of a pilot program for the implementation of agricultural best management practices (BMP's) to control nonpoint sources of pollution. The program was performed within the Honey Creek Watershed, North Central Ohio. The evaluation includes considerations of: (1) project accomplishment by contract tasks and (2) method of accomplishment.		

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